HVAC SYSTEMS: UNDERSTANDING THE BASICS

Sheet Metal and Air Conditioning Contractors'
National Association
4201 Lafayette Center Drive
Chantilly, VA 20151-1209
www.smacna.org

Thomas E. Glavinich, D.E.
The University of Kansas

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UNDERSTANDING THE BASICS

**SHEET METAL AND AIR CONDITIONING CONTRACTORS'
NATIONAL ASSOCIATION, INC.**

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PREFACE

INTRODUCTION

The purpose of a heating, ventilating, and air conditioning (HVAC) system is to establish an indoor environment within which building inhabitants can live, work, and play. The indoor environment impacts the quality of life, productivity, and well being of building inhabitants. As people spend an increasing amount of time inside buildings, HVAC systems and their associated control systems are becoming more important. As a result, the complexity and cost of HVAC systems for commercial and institutional buildings is increasing. HVAC systems represent an increasingly larger percentage of the construction dollar. In addition, these systems represent a significant ongoing operation and maintenance cost for the owner over the life of the building.

The HVAC contractor is the firm that is responsible for the installation of the complete HVAC system for the owner in accordance with the scope of work defined by the contract documents. The HVAC contractor is typically responsible for planning the installation, procuring the necessary materials and equipment, determining the means and methods of installation, performing the installation, and starting up and commissioning the HVAC system. The HVAC contractor may self perform all of the HVAC work or may subcontract portions of the work such as piping, insulation, testing, adjusting, and balancing (TAB), or system controls. For a design-build project, the HVAC contractor would also be responsible for the HVAC system design.

The increasing complexity of HVAC systems and their importance in modern buildings makes it imperative that the HVAC contracting firm's office and field personnel understand not just the part of the system they normally work on but the entire system, how the various subsystems and components work, and the interrelationship between the different subsystems and components.

MANUAL PURPOSE

The purpose of *HVAC Systems: Understanding The Basics* is to provide an overview of HVAC systems, the equipment and components that comprise them, and how they work. This manual is not intended to address HVAC design and does not address building heating or cooling load calculations, equipment sizing, or system layout. Instead, this manual is intended for use by the HVAC contracting firm's field and office personnel that need an overall understanding of HVAC systems for bidding and negotiating projects, planning and scheduling work, fabrication and installation of HVAC system equipment and components, and system commissioning and project closeout. This manual may also be helpful to general contractor and construction management firm personnel who want to know more about HVAC systems and equipment as well as other specialty contracting firms such as electrical contracting firms that need to interface with HVAC contractor.

MANUAL OVERVIEW

This manual is divided into ten chapters and four appendices. Chapter I provides an introduction to HVAC systems and this manual. This chapter starts out with a discussion of what an HVAC system is and discusses why buildings need HVAC systems. In addition, this chapter provides a brief history of HVAC and discusses its increasing importance in 21st Century buildings. Chapter I concludes with an overview of the manual.

The properties of moist air that are key to understanding space conditioning processes and HVAC systems are introduced in Chapter II. This chapter starts by defining temperature and humidity and how these basic properties of moist air are measured. Psychrometry is defined and the psychrometric chart is used to introduce important properties of moist air including dry-bulb temperature, wet-bulb temperature, dew-point temperature, percent relative humidity, humidity ratio, and air specific volume and density as well as how these key space conditioning variables interact. Heat transfer, heat transfer mechanisms, and heat transfer units are introduced next because a basic understanding of heat transfer concepts is key to understanding HVAC equipment and systems. Moist air energy content is then covered which includes sensible heat, latent heat, and enthalpy. All of this sets the stage for understanding space conditioning processes, HVAC equipment, and HVAC systems covered throughout the remainder of this manual.

Chapter III builds on Chapter II by introducing the basics of HVAC systems. The purpose of an HVAC system is covered first and lays the foundation for the remainder of the chapter. The concept of an HVAC zone is then defined along with airflow. Thermal comfort is then discussed along with the importance of indoor air quality (IAQ) and HVAC energy use. The four basic elements of any HVAC system are presented followed by a discussion of space conditioning methods and HVAC system categories.

Unitary HVAC systems are covered in Chapter IV because unitary systems are self-contained units with all the HVAC system elements discussed in Chapter III. Unitary HVAC systems include a wide variety of different types of air-conditioning units that include their own integral refrigeration cycle and range from residential widow air conditioning units to rooftop units used for commercial and light industrial applications. Most people are familiar with unitary HVAC systems and the fact that they are fully self-contained makes it easier to see the interrelationship between the elements and serves as a good introduction to central and distributed HVAC systems. This chapter covers the various types of unitary HVAC systems and their operation. A detailed overview of the mechanical refrigeration cycle is also provided that will be used again in Chapter VI where central cooling equipment is covered. This chapter finishes with a discussion of unitary heat pumps.

Central heating equipment is covered in Chapter V and includes both furnaces and boilers. Furnaces are discussed first because most people are familiar with furnaces due to their use in residential and light commercial buildings. A discussion of boilers, boiler types, and associated equipment including boiler circulating pumps and deaerators follows furnaces.

Chapter VI covers central cooling equipment that includes chillers and cooling towers. This chapter starts with a detailed discussion of chiller operation including the chiller refrigeration cycle. Types of chillers and chiller components commonly used to supply chilled water in commercial and institutional buildings are covered next. Lastly, cooling tower operation, types, and construction are discussed.

Hydronic distribution systems where water is used as the heat transfer medium in central HVAC systems are discussed in Chapter VII. Both hot and chilled water distribution systems are covered along with a detailed discussion of common hydronic piping arrangements. Convection terminal units that condition the space are also covered in detail in this chapter.

Air distribution for HVAC systems is covered in Chapter VIII. Chapter VIII starts by discussing the purpose and operation of an air-distribution system that sets the stage for the remainder of this chapter. Sections that discuss each of the components that comprise an air distribution system follow these introductory sections. A section on fans covers fan operation and briefly discusses the various types of fans found in commercial and institutional buildings and their construction and characteristics. Sections that cover metal ductwork, duct dampers, air terminal units, air outlets and inlets, and air cleaning devices follow this. Chapter VIII ends with a discussion of testing, adjusting, and balancing (TAB) air distribution systems.

Chapter IX addresses central HVAC systems that are prevalent in large commercial and institutional buildings. A central HVAC system is one where the heating source, cooling source, or both are centrally located and serve a significant part of the building. Following a general discussion of central HVAC system layout and operation, the five primary central HVAC subsystems are presented and discussed. Variable-air-volume (VAV) central HVAC systems are the focus of this chapter because they are the most common system used today. Constant volume central HVAC systems are also covered because constant volume HVAC systems are used where a constant supply of conditioned air is required in certain occupancies.

HVAC system control is covered in Chapter X. HVAC systems seldom operate at their design point and both the external and internal thermal loads are constantly changing. The purpose of HVAC system control is to ensure that the HVAC system can effectively and efficiently adapt to changing outdoor conditions as well as changing internal occupancy and activities. Chapter X starts with a discussion of the purpose of the control system followed by description of HVAC control system operation and definitions of control system elements. Control loops and example control systems are then presented. Types of HVAC control systems are then discussed followed by a discussion of building automation and control. This chapter finishes with a discussion of open-architecture HVAC system control.

Four appendices follow Chapter X. Appendix A provides a glossary of HVAC terms and abbreviations used throughout this manual. HVAC references and resources published by SMACNA that can be used for further information and study are provided in Appendix B. Division 23 of the 2004 Construction Specifications Institute (CSI) *MasterFormat*™ is provided in Appendix C for reference. Finally, Appendix D shows photos of various equipment and components.

CHAPTER I
INTRODUCTION TO HVAC SYSTEMS

1.1 INTRODUCTION

This chapter provides an introduction to heating, ventilating, and air-conditioning (HVAC) systems and this manual. This chapter starts out with a discussion of the purpose of an HVAC system and then discusses the role of the HVAC contractor and why an understanding of the complete HVAC system is very important. This is followed by the purpose of this manual and finally by an overview of the remaining nine chapters and three appendices that comprise this manual.

1.2 HVAC SYSTEM PURPOSE

The purpose of a heating, ventilating, and air conditioning (HVAC) system is to establish an indoor environment within which building inhabitants can live, work, and play. The indoor environment impacts the quality of life, productivity, and well being of building inhabitants. As people spend an increasing amount of time inside buildings, HVAC systems and their associated control systems are becoming more important. As a result, the complexity and cost of HVAC systems for commercial and institutional buildings is increasing. HVAC systems represent an increasingly larger percentage of the construction dollar. In addition, these systems represent a significant ongoing operation and maintenance cost for the owner over the life of the building.

1.3 HVAC CONTRACTOR DEFINED

The HVAC contractor is the firm that is responsible for the installation of the complete HVAC system for the owner in accordance with the scope of work defined by the contract documents. The HVAC contractor is typically responsible for planning the installation, procuring the necessary materials and equipment, determining the means and methods of installation, performing the installation, and starting up and commissioning the HVAC system. The HVAC contractor may self perform all of the HVAC work or may subcontract portions of the work such as piping, insulation, testing, adjusting, and balancing (TAB), or system controls. For a design-build project, the HVAC contractor would also be responsible for the HVAC system design. As a result, the increased complexity of HVAC systems today, the HVAC contractor needs to have an overall understanding of HVAC systems and how they operate.

1.4 PURPOSE OF THIS MANUAL

The purpose of this manual is to provide an overview of HVAC systems used in residential, commercial, and institutional buildings including system operation and the components that comprise these systems. This manual can be used for self-study, group training, or reference. This manual is intended to complement SMACNA's *HVAC Bid Specification Manual* that was developed to help HVAC contractors prepare bids and proposals for HVAC systems. In addition, this manual is also intended to complement SMACNA's *HVAC Systems Applications Manual* by providing a basic introduction to HVAC systems and operation.

1.5 OVERVIEW OF THIS MANUAL

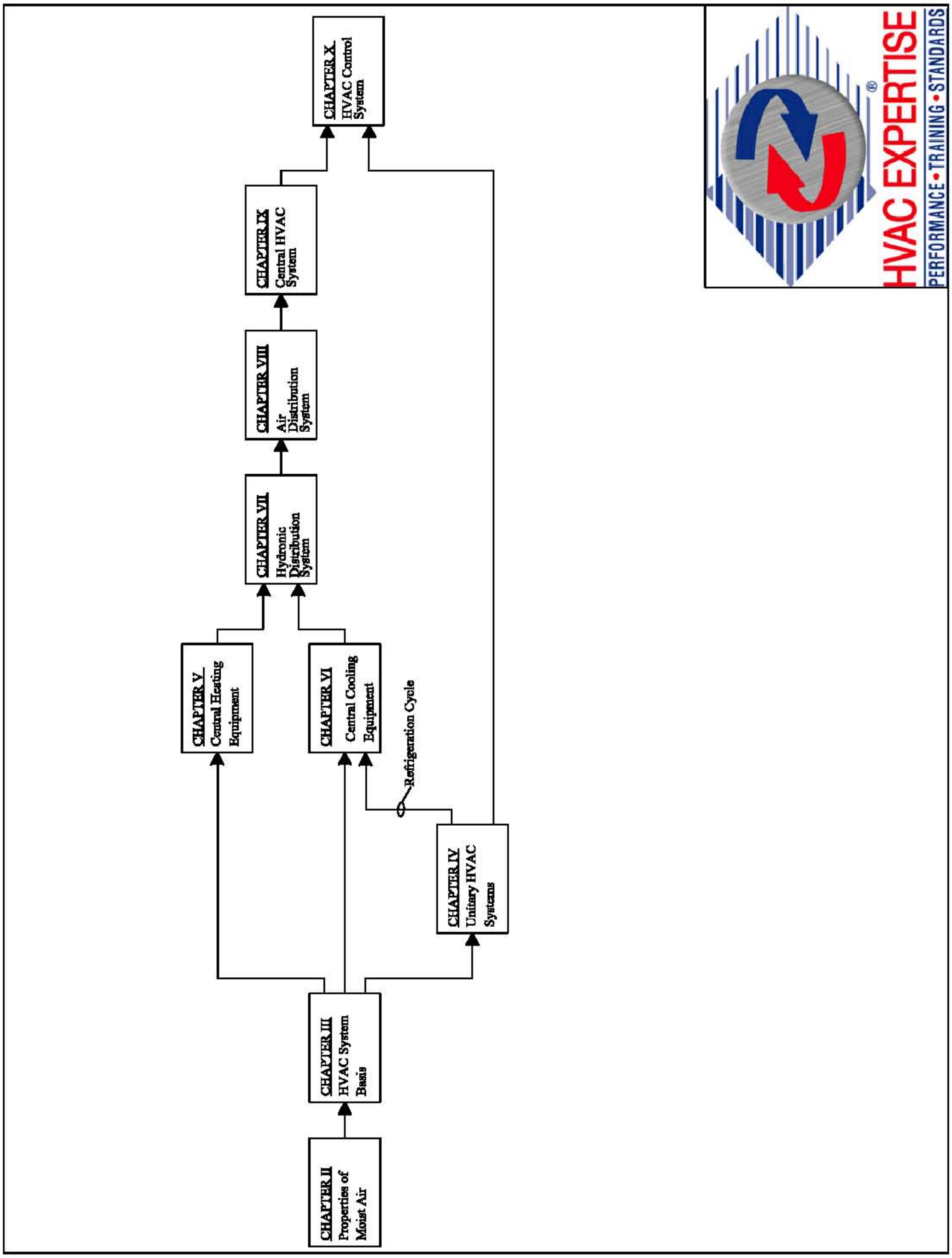
Figure 1-1 provides a flow chart illustrating how this manual is structured and how the remaining nine chapters interrelate to one another. As can be seen from Figure 1-1, Chapter II starts with a discussion the properties of moist air that are controlled by HVAC systems to provide a comfortable thermal environment for building occupants. Chapter III builds on Chapter II by introducing the basics or HVAC systems, defining human comfort in terms of the properties of moist air and discussing how HVAC systems control the properties of moist air. Chapter III is also important because it addresses energy use by HVAC systems and the tradeoffs between human comfort and energy efficiency.

Unitary HVAC systems are covered next in Chapter IV because these systems are common in residential and light commercial buildings and will be familiar to readers. Unitary HVAC systems are also self-contained units that can be used to illustrate the mechanical refrigeration cycle as well as illustrate in physical terms Chapter III's HVAC block diagram elements. Central heating and cooling equipment are then covered in Chapters V and VI, respectively. These chapters follow Chapter III and draw parallels wherever possible between the familiar unitary HVAC equipment and central plant HVAC equipment to help the reader understand that basic system operation has not changed only the scale and heat transfer media.

Building on the central heating and cooling chapters, Chapter VII covers basic hydronic distribution systems and Chapter VIII covers basic air distribution systems in buildings including fan laws, fan operation, and the use of variable frequency drives. Chapter IX covers central HVAC as a system by bringing together previous four chapters that deal with central heating, central cooling, hydronic distribution, and air distribution as subsystems. In keeping with this manual's purpose of providing the basics of HVAC system operation, only variable-air-volume (VAV) systems are covered in Chapter VIII because these systems are the most common in today's commercial and institutional buildings. A detailed discussion of the other types of air distribution systems along with a comparison between them is left for SMACNA's *HVAC Systems Applications Manual*. Finally, Chapter X introduces HVAC system control system using the system perspective developed in Chapter IX.

Four appendices are also included in this manual. Appendix A provides a glossary of HVAC terms for reference. The outline of CSI's 2004 MasterFormat^{TM} for Division 26/HVAC is provided in Appendix B. HVAC references and resources published by SMACNA are contained in Appendix C. Finally, photos of various equipment and components are provided in Appendix D.

Figure 1-1 Manual Chapter Flow Chart



CHAPTER II
PROPERTIES OF MOIST AIR

2.1 INTRODUCTION

This chapter introduces the properties of moist air that are key to understanding space conditioning processes and HVAC systems. This chapter starts by defining temperature and humidity and how these basic properties of moist air are measured. Psychrometry is defined and the psychrometric chart is used to introduce important properties of moist air including dry-bulb temperature, wet-bulb temperature, dew-point temperature, percent relative humidity, humidity ratio, and air specific volume and density as well as how these key space conditioning variables interact. Moist air energy content is then covered which includes sensible heat, latent heat, and enthalpy. All of this sets the stage for a discussion and analysis of both simple and practical space conditioning processes using the psychrometric chart.

2.2 AIR CHEMISTRY

2.2.1 Air Ingredients

Air near the surface of the earth consists of a mixture of three ingredients that include the following:

- Standard Dry Air
- Water Vapor
- Other Constituents

The following paragraphs will discuss each of these three ingredients.

2.2.2 Standard Dry Air

Standard dry air is composed of a variety of gases but it primarily consists of oxygen and nitrogen that make up about 99 percent of air by volume. A breakdown of dry air by gas as a percent of volume is as follows:

GAS	PERCENT BY VOLUME
Nitrogen	78.080
Oxygen	20.950
Noble Gases	0.930
Carbon Dioxide	0.038
Total	**100.000**

As can be seen from the table, nitrogen and oxygen make up about 78 percent and 21 percent of the atmosphere by volume, respectively. The six noble gases are helium, neon, argon, krypton, xenon, and radon and they comprise about one percent of the air by volume. Finally, carbon dioxide makes up only a fraction of one percent of dry air but it is a very important consideration in HVAC systems and impacts IAQ and ventilation requirements.

2.2.3 Water Vapor

Water vapor is the second ingredient in air and it can vary greatly from almost nothing to about 5 percent by volume. When the amount of water in air is very low which can get down as low as 0.5 percent by volume, air is referred to as dry air. When air contains a sufficient amount of water vapor that is noticeable to people, the air is referred to qualitatively as humid. Humidity is an important consideration in human thermal comfort and an important factor in HVAC system design, installation, and operation.

2.2.4 Other Constituents

Other constituents can also be found in the air that reflects local conditions. These other constituents can simply be an annoying odor or could be a chemical compound like carbon monoxide that can become an irritant or a health risk when they reach a certain concentration in the air. These chemical compounds can occur naturally, they can be the byproduct of combustion including cooking, result from off gassing by building materials and furnishings, or caused by the use adhesives, coatings, pesticides, or other chemicals in a building. In addition, there can be particulate matter in the air that can also cause irritation and be a health risk to occupants. This particulate matter could be inanimate such as dust or it could be living organisms like bacteria, viruses, mold, and small insects in the air. When known to be present and possible, the HVAC system should mitigate the impact of these constituents on occupants by increasing ventilation to reduce their concentration or removing them from the air stream using air cleaning devices when possible.

2.3 AIR TEMPERATURE

2.3.1 What Is Temperature?

For people, the term temperature is a measure of the degree of “hotness” or “coldness” that they feel when they come in contact with an object or enter a space. Temperature is felt by people and is an important consideration in both human comfort and HVAC system design and operation. Temperature as it relates to comfort is subjective and depends on a variety of physical variables as will be discussed in Section III. However, everyone has experienced the situation where they are hot or cold in a space when other people that have similar physical characteristics and clothing experience the “temperature” of an object or space much differently. Therefore, there needs to be a more exact method of defining temperature and measuring it.

At the microscopic level, temperature can be defined as the measure of the average translational kinetic energy that is associated with the disordered motion of the atoms or molecules that make up an object or substance. From an HVAC standpoint, the important thing is that this kinetic energy at the microscopic level can and is readily transferred between objects and substances and this transfer makes HVAC systems possible. Thermodynamic energy always flows from the "hotter" object or substance to the "cooler" object or substance because the "hotter" object or substance has more energy. If "hotter" and "cooler" objects or substances are left in contact with one another long enough they will reach thermodynamic equilibrium. Two objects or substances will be at the same temperature when they reach thermodynamic equilibrium. People in contact with the two objects or substances will perceive them to have the same temperature.

2.3.2 Temperature Scales

Temperature is measured by a thermometer which eliminates human subjectivity and provides an objective way of determining the temperature of an object or substance. There are a number of temperature scales that have been developed and are in use today. Many of these temperature scales were developed for specific uses in science and industry and are not used in everyday life or in HVAC system design and operation. The three most common temperature scales used in the United States today are as follows:

- Fahrenheit
- Celsius
- Kelvin

Each of these temperature scales can be used to measure the temperature of an object or a substance. The only difference between the three is the scale established between two standard temperature points. In order to establish a temperature scale or develop relationships between two different temperature scales, two standard reference temperature points must be established. The two standard temperature reference points that are commonly used to establish and relate temperature scales are the freezing and boiling of water at standard pressure.

Standard Pressure. Standard pressure is the average atmospheric pressure at sea level which will support a column of mercury that is 29.921 inches (760 mm) high or 14.696 pounds per square inch absolute (psia). Standard pressure is usually referred to as one atmosphere.

Fahrenheit Temperature Scale. The Fahrenheit temperature scale is named after Gabriel Fahrenheit who was the German physicist that proposed it in 1724. Temperature is expressed as degrees Fahrenheit (^{o}F) on this temperature scale. The melting point of ice is 32^{o}F and the boiling point of water is 212^{o} F at standard pressure.

Celsius Temperature Scale. The Celsius temperature scale was formerly referred to as the centigrade temperature scale. The Celsius temperature scale is named after Anders Celsius who was a Swedish astronomer and developed the first version of the temperature scale that was named after him. Temperature is expressed as degrees Celsius (^{o}C) on this temperature scale. On the Celsius temperature scale the melting point of ice occurs at 0^{o}C and the boiling point of water occurs at 100^{o}C at standard pressure.

Kelvin Temperature Scale. The Kelvin temperature scale was named after Lord Kelvin who was the British inventor and scientist that developed it in the 19th Century. Zero degrees on the Kelvin temperature scale is defined as absolute zero which is the inferred temperature where all molecular movement stops in an object or substance and therefore the object or substance has no temperature. Temperature on the Kelvin temperature scale is expressed in degrees Kelvin or just simply as Kelvin (K). The Kelvin temperature scale is graduated exactly the same as the Celsius temperature scale and one degree difference in temperature on the Kelvin temperature scale is the same as the Celsius temperature scale. However, using inferred absolute zero as the reference point, water freezes at standard pressure on the Kelvin temperature scale at 273.16K and boils at 373.16K which represents exactly a 100 degree spread just as it does on the Celsius temperature scale.

2.3.3 Temperature Scale Relationships

As noted above, the three temperature scales can all be related through the temperature scale points of where water freezes and boils at standard pressure. These temperature scale points were noted in the previous section and are summarized in the following table:

	ABSOLUTE ZERO	**WATER**	
		FREEZES	**BOILS**
FAHRENHEIT	-459.7 ^{o}F	32 ^{o}F	212 ^{o}F
CELSIUS	-273.16 ^{o}C	0 ^{o}C	100 ^{o}C
KELVIN	0 K	273.16 K	373.16 K

The relationships between these three temperature scales are summarized in the following table:

TO GET	**GIVEN**		
	^{o}F	**^{o}C**	**K**
^{o}F		$t_F = \frac{9}{5} t_C + 32$	$t_F = \frac{9}{5} t_K - 459.69$
^{o}C	$t_C = \frac{5}{9}(t_F - 32)$		$t_C = t_K - 273.16$
K	$t_K = \frac{5}{9}(t_F + 459.69)$	$t_K = t_C + 273.16$	

2.3.4 Operative Temperature

Operative temperature (t_{op}) or mean radiant temperature (MRT) is the temperature of a uniform black enclosure in which a solid body or occupant would exchange the same amount of radiant heat as in the existing non-uniform environment. Operative temperature is measured with a globe thermometer.

2.4 AIR HUMIDITY

Humidity is water vapor in a given space. Absolute humidity is the weight of water vapor per unit air volume.

2.5 MOIST AIR PHYSICAL PROPERTIES

2.5.1 Key Moist Air Physical Properties For HVAC

The physical properties of air-water mixtures can be measured by the following characteristics:

- Dry-Bulb Temperature
- Wet-Bulb Temperature
- Dew-Point Temperature
- Relative Humidity
- Humidity Ratio

2.5.2 Dry-Bulb Temperature

The dry-bulb (DB) temperature of the air is the temperature that is measured by an ordinary thermometer that is freely exposed to the air but shielded from both radiation and moisture.

2.5.3 Wet-Bulb Temperature

Wet-Bulb Temperature. Wet-bulb (WB) temperature is measured using a WB thermometer. A WB thermometer is a standard thermometer that has its bulb wrapped in a piece of cloth that is typically referred to as a wick or sock. The wick is wetted with water is the temperature measured with air flowing rapidly over the thermometer. The water evaporate and cools the thermometer bulb and the measured temperature is referred to as the WB temperature. The WB temperature will always be less than the DB temperature except at the dew point when the WB temperature is equal to the DB temperature.

WB Depression. The difference between the DB temperature and the WB temperature is referred to the WB depression. WB depression is a measure of the dryness of the air. The dryer the air, the greater the difference between the DB temperature and the WB temperature or WB depression.

2.5.4 Dew-Point Temperature

The dew-point (DP) temperature is the temperature at which the water vapor in a space will begin condensing for a given humidity and pressure. The DP temperature can also be defined as the temperature corresponding to saturation (100 percent relative humidity) for a given absolute humidity at constant pressure.

2.5.5 Percent Relative Humidity

Relative humidity (RH) is the ratio of the amount of water vapor in the air to the water vapor present in saturated air at the same temperature and barometric pressure. The relative humidity of the air in a space can be determined from the measured DB and WB temperatures by calculation or using a psychrometric chart as will be discussed later in this section.

2.5.6 Humidity Ratio

Humidity ratio is the ratio of the mass of water vapor to the mass of dry air contained in a sample. Humidity ratio is usually expressed in grains of moisture per pound of dry air (grams of water per kilogram of dry air) and is the ratio of the mass of water vapor to the mass of dry air in a space.

2.6 PSYCHROMETRIC CHART

2.6.1 What Is Psychrometry?

Psychrometry is the science of air-water mixtures.

2.6.2 Psychrometric Chart

A psychrometric chart is a graphical representation that shows the relationship between the five metrics that can be used to describe the thermophysical properties of moist air at a particular barometric pressure. Figure 2-1 provides an example psychrometric chart at sea level with a standard barometric pressure of 29.921 inches of Mercury.

By knowing any two of the five metrics, the other three can be found from the psychrometric chart. For example, given a dry bulb temperature of 85°F and a wet bulb temperature of 70°F, the other four metrics can be read directly from the psychrometic chart as shown in Figure 2-2 as follows:

Relative Humidity = 47%

Humidity Ratio = 42 Grains Of Moisture/Pound Of Dry Air

Dew Point Temperature = 37°F

Figure 2-1 Typical HVAC Psychrometric Chart

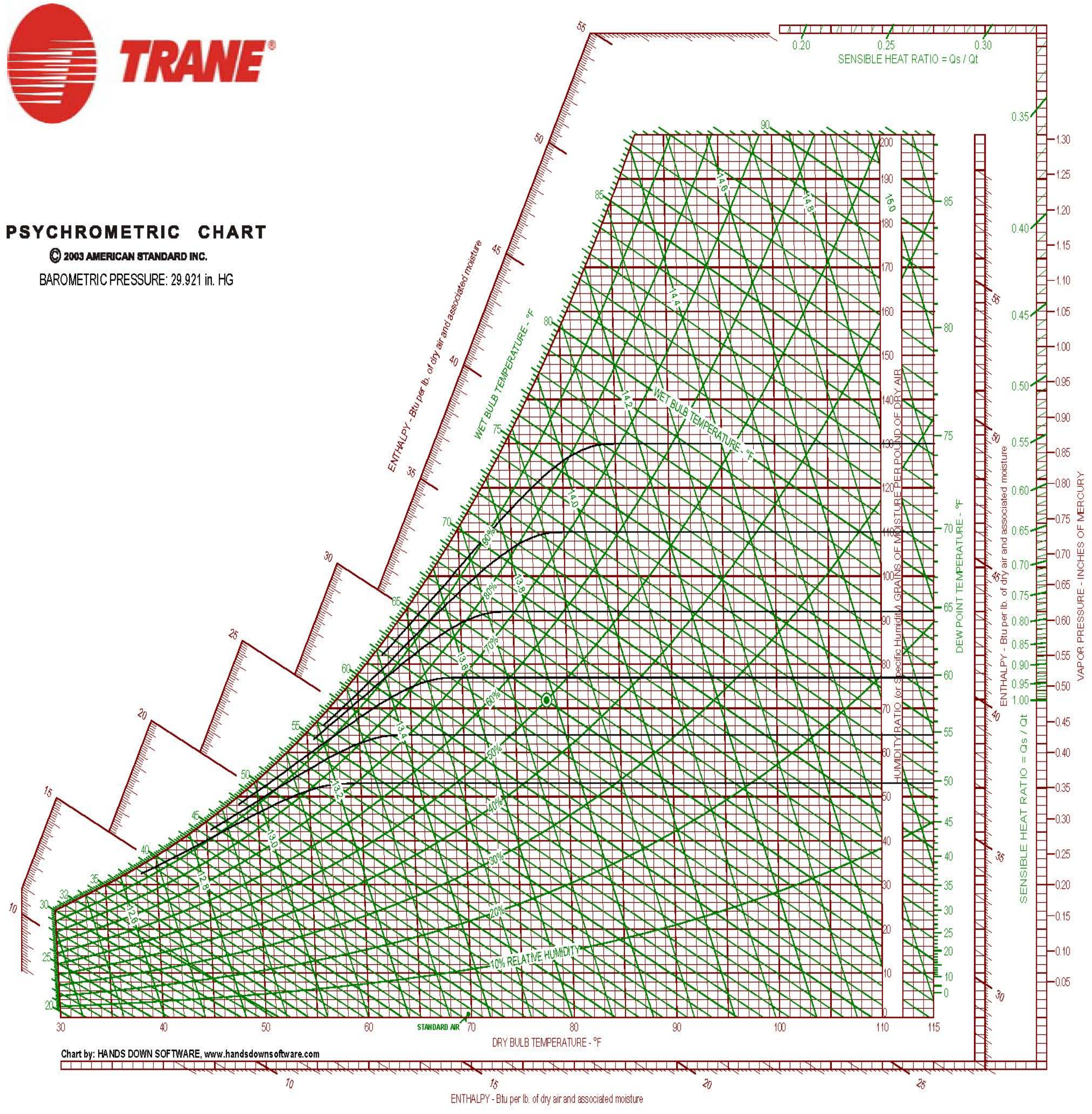
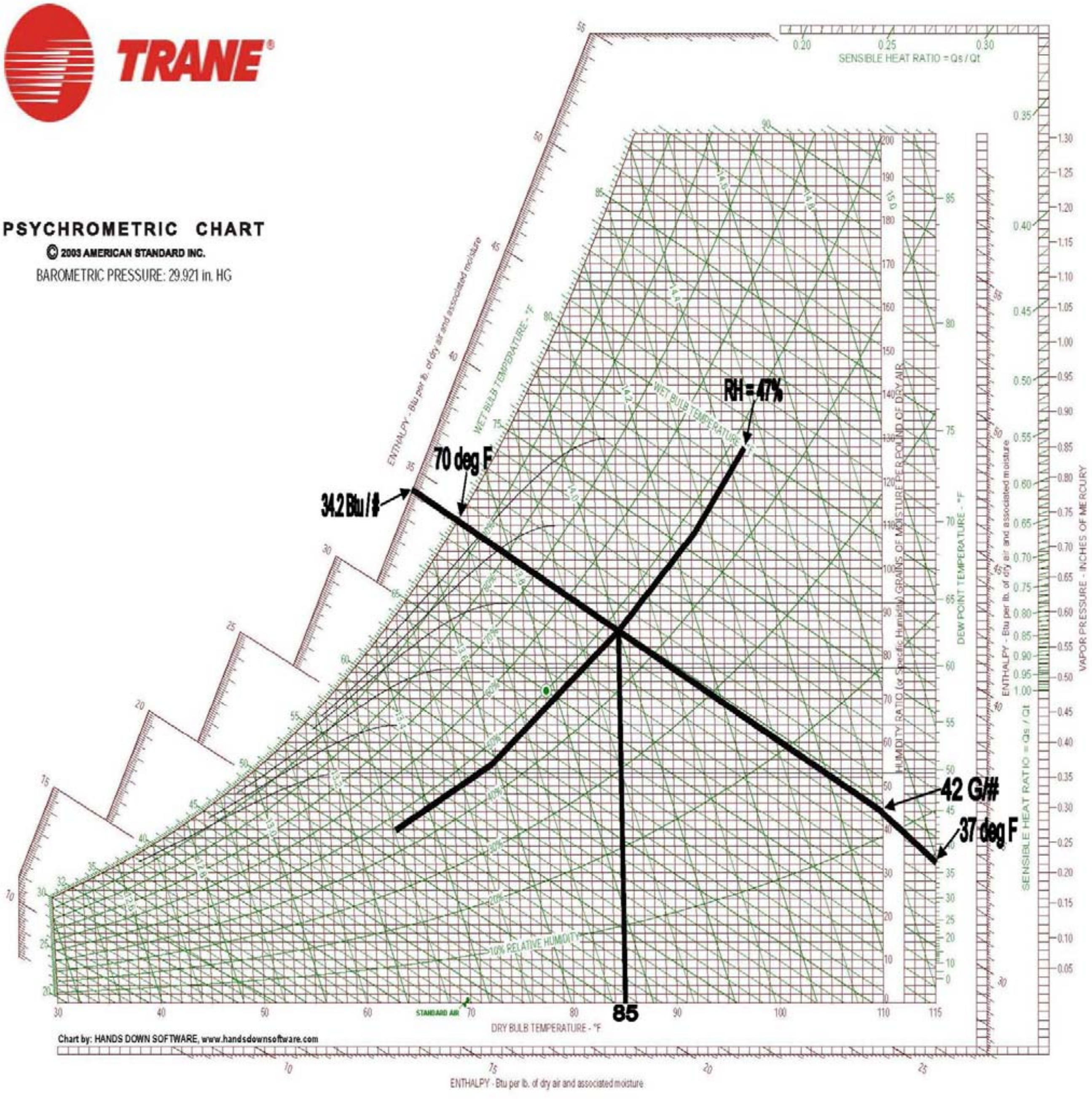


Figure 2-2 Psychrometric Chart Example



2.7 HEAT TRANSFER METHODS

2.7.1 Heat Transfer Direction

The fundamental principle of heat transfer is that heat always flows from a warmer body or substance to a cooler body or substance. The reason for this is that the warmer body or substance is at a higher energy level and energy must flow to the cooler body or substance that is at a lower energy level. Energy cannot flow from a cooler body or substance to a warmer body or substance in the same way that a liquid cannot flow naturally from a lower elevation to a higher elevation. Allowed to flow naturally, liquids will always flow from a higher point with higher potential energy to a lower point with lower potential energy. Heat transfer is the same and is actually about energy transfer.

2.7.2 Three Methods Of Heat Transfer

There are three methods by which heat can be transferred from a warmer body or substance to a cooler body or substance. The three methods of heat transfer are as follows:

- Conduction
- Convection
- Radiation

The following paragraphs will discuss each of these three heat transfer methods.

2.7.3 Conduction

Conductive heat transfer occurs when heat is transferred between two bodies or substances that are in physical contact with one another. Conduction occurs at the contact point between the warmer and cooler bodies or substances. As discussed above, the warmer body or substance is at a higher energy level than the cooler body or substance that it is in contact with. As a result of this direct contact, the higher energy atoms or molecules in the higher temperature body or substance interact at the contact boundary with the lower energy atoms or molecules of the lower temperature body or substance and energy is transferred.

Energy throughout the warmer body or substance flows toward the contact boundary and into the cooler body or substance. If no additional heat energy is added to the warmer body or substance, the two bodies will eventually reach thermal equilibrium and be at the same temperature. The rate of heat flow between the two bodies or substances is determined by their respective thermal conductivities, difference in temperature between the two, and the physical dimensions of the contact area.

2.7.4 Convection

Like conduction, convection relies on the physical contact between the higher temperature body or substance and the lower temperature body or substance for heat transfer. However, with conduction the physical contact between the two bodies or substances is fixed and with convection one body or substance is in motion passing over or through the other body or substance.

An example of convective heat transfer is the use of a hot water or steam radiator to warm a room. From a convection standpoint, the way that a radiator works is that cooler air in contact with warmer surface of the radiator warms and becomes lighter than the surrounding cooler air. This occurs because in heating the air, the air molecules move further apart reflecting their increased energy level making the warmer air less dense and lighter than the same volume of cooler air. As a result of this, the warmer air is more buoyant and rises displacing the cooler heavier air above it. The displaced cooled air is then forced into contact with the radiator and it is warmed and the cycle continues as the warmed air circulates through the room warming room surfaces, furnishings, and people that it comes in contact with. This transfer of energy results in the warmed air cooling and becoming more dense and cycled back through the radiator where it is warmed again.

In this example, air circulates through the radiator as a result of buoyancy where heated air rises because it is less dense than the surrounding air and displaces the denser cool air. This displacement in turn forces the cooler air through the radiator naturally causing it to be warmed and maintaining the cycle. When a substance circulates naturally as it does with the simple radiator in this example, the method of heat transfer is referred to as natural convection. If a mechanical or chemical means is used to force a substance to flow over or through another body to cause or enhance convective heat transfer, the method of heat transfer is referred to as forced convection. Forced convection is typically achieved in HVAC systems by using of fans for moving air or pumps for moving liquids like water or gases like refrigerants.

2.7.5 Radiation

Radiation is the third method of heat transfer between two bodies or substances. Unlike conduction and convection, there is no physical contact between the two bodies or substances with radiant heat transfer. With radiation, energy is transferred via electromagnetic radiation from a warmer object to a cooler object and no heat transfer medium is required. The sun and earth are a good example of radiant energy transfer where the sun’s energy in the form of electromagnetic radiation travels through space that is a vacuum devoid of any heat transfer media and warms the earth. Similarly, when the electromagnetic energy comes in contact with an object or substance, the atoms or molecules absorb the energy and heating results. Radiant heating used in HVAC systems include electric heating elements such as resistive coils, infrared lamps, and even the simple radiator in the previous example. Not only does the simple radiator heat the air passing through it but it also radiates energy that heats surrounding room surfaces, furnishings, and people.

2.7.6 HVAC Is All About Heat Transfer

HVAC is all about heat transfer and all HVAC systems are designed to move heat from one place to another using conduction, convection, radiation, or a combination of these heat transfer methods. With air conditioning and refrigeration, heat is extracted from the area that needs to be cooled and rejected to the outside, transferred to another area that requires heat, or a combination of the two. Similarly, heat is delivered to an area that needs to be heated by one or more of these heat transfer methods.

2.8 HEAT TRANSFER UNITS

2.8.1 British Thermal Unit (Btu)

A British thermal unit (Btu or sometimes BTU) is a measure of energy. One Btu is the quantity of heat energy needed to raise the temperature of one pound of water $1^{o}F$ at a constant pressure of one atmosphere. In terms of other common measures of energy, one Btu is approximately equal to the following number of joules (J):

$$1 \text{ Btu} = 1055 \text{ J}$$

In turn, one joule is about equal to 0.2388 calories (Cal) leading to the following relationship between British thermal units and calories:

$$1 \text{ Btu} = 252 \text{ Calories}$$

2.8.2 Btu Per Hour

Power is defined as energy transfer or conversion per unit of time. In heat transfer, the units of power are typically expressed in Btu per hour (Btu/hr).

2.8.3 Conversion To Electrical Units

Since most HVAC equipment is electrically driven is it often convenient to convert heat transfer units used in designing and sizing HVAC systems and equipment to electrical units. Including adjustments for efficiency and other factors, the conversion from thermal energy and power units to electrical energy and power units can be used to estimate the amount of electrical energy that will be used by the equipment, process, or system as well as the electrical power requirements. This information can be used for performing preliminary economic studies and energy analyses as well as conceptual electrical distribution system design.

As noted above, British thermal units are a measure of thermal energy. As a result, a British thermal unit can be related to a kilowatt hour (kWh) or 1,000 watt hours. A kilowatt hour is the unit of electrical energy that is commonly used by electric utilities to measure and charge for electric energy use. The fact that a kilowatt hour is equivalent to 3,600,000 joules leads to the following relationship between thermal and electrical energy units:

1 kWh = 3412 Btu

Similarly, British thermal units per hour or Btu/hr is a measure of the rate of energy transfer or power. Thermal power can be equated to kilowatts (kW) which is 1000 watts and the common unit electrical power that is used by utilities to measure and charge for electricity demand in larger commercial, institutional, and industrial facilities. It is also the basis for sizing electrical distribution equipment when adjusted for the power factor of the mechanical equipment yielding apparent power of kilovoltamperes (kVA). British thermal units per hour can be related to kilowatts by dividing both sides of the equality relating kilowatt hours and British thermal units by one hour. The resulting relationship between British thermal units and kilowatts is as follows:

1 kW = 3412 Btu/hr

2.9 MOIST AIR ENERGY CONTENT

2.9.1 Change Of State

In order to understand moist air energy content, the concept of material states or phases and state or phase change needs to be understood. The terms “state” or “phase” are synonymous when referring to a change in a material’s state or phase and the term “state” will be used in this manual. The three states of any physical substance are classified as follows:

- Solid
- Liquid
- Vapor Or Gas

Conceptually, the distance between the atoms or molecules that make up a material determines the state of that material. In other words, the closer together that atoms or molecules that make up the material are packed together the denser the material and the less energy these atoms or molecules have. When a material is in its solid state, the atoms or molecules that make up the material are in a low energy state and close together forming a solid structure. As energy is added in the form or heat, the atoms or molecules separate and the material changes from its solid state to its liquid state. With the addition of more energy in the form of heat, the atoms or molecules that comprise the material in its liquid state separate further and the material becomes less dense and changes state to its vapor or gas state or phase. The terms “vapor” and “gas” are interchangeable and in this manual the term “vapor” will be used because this term is most often used to describe water in its gaseous state.

As can be seen from the above discussion, energy is required to change a material’s state from solid to liquid and from liquid to vapor. As a result, the change of state from both solid to liquid and liquid to vapor are both referred to as endothermic indicating that energy in the form of heat must be added to affect these changes of state. On the other hand, a material changing state from vapor to liquid or from liquid to solid releases energy because the atoms or molecules that comprise the material are giving up energy as they come closer together and the material becomes increasingly dense with each change of state. As a result, the change of state from vapor to liquid or from liquid to solid for a material is said to be exothermic because energy is given up in the state changes.

2.9.2 Sensible Heat

Sensible heat is also referred to as enthalpy. Sensible heat is the heat that is absorbed by a material during a change in temperature that does not include a change in state. Sensible heat is any heat transfer that causes a change in temperature in a material. Heating and cooling of moist air that can be measured with a thermometer is sensible heat. Heating or cooling coils that simply increase or decrease the air temperature without a changing the moisture content of the air are examples of sensible heat. Sensible heat can be transferred by conduction, convection, radiation or any combination of the three heat transfer methods.

2.9.3 Latent Heat

Latent heat is also referred to as the heat of transformation. Latent heat is the amount of heat absorbed or released by a material undergoing a change of state without a change in temperature. The heat of transformation is referred to as "latent heat" because there is no change in temperature associated with the phase change. Examples of latent heat include the heat required to change water from its solid state as ice to its liquid state at 32^{o}F or required to change from its liquid state to its vapor state when it boils at 212^{o}F. Conversely, latent heat is the amount of heat released when these phase changes are reversed and vapor turns to water and water turns into ice.

Latent heat is a property of a material. The amount of latent heat required for a change of state varies by material. Each material has the following two latent heats associated with it:

- Heat Of Fusion
- Heat Of Vaporization

The heat of fusion refers to the amount of heat in British thermal units required to melt a material and change it from its solid state to its liquid state. For water, the heat of fusion required to convert one pound of ice to water at 32^{o}F and 1 atmosphere pressure is 144 Btu. As a result, the latent heat of fusion for ice is 144 Btu/lb. Similarly, the heat of vaporization is the amount of heat in British thermal units required to change a material's state from liquid to gas. The heat of vaporization required to convert one pound of water to vapor at 212^{o}F requires 970 Btu. Therefore, water's latent heat of vaporization is 970Btu/lb. Reversing the phase change processes requires the same energy per pound.

2.9.4 Relationship Between Sensible & Latent Heat

Figure 2-3 illustrates the relationship between sensible and latent heat of water as it passes from being ice to liquid and from liquid to vapor. The abscissa or x-axis of Figure 2-3 is the heat energy expressed in British thermal units required to raise a pound of water 1°F during sensible heating in a particular state or required to transform a pound of water in a particular state during latent heating. The ordinate or y-axis of Figure 2-3 gives the temperature of the water in its various states at every step along the way.

Starting at 0°F, the water is ice and requires 0.5 Btu/lb of sensible heating to increase the temperature one pound of ice by 1°F. As shown in Figure 2-3, 16 Btu of sensible heating is required to increase the temperature of the ice from 0°F to 32°F. Once the pound of ice reaches 32°F, latent heating takes over and 144 Btu of heat is used to transform the ice to water. This is water's latent heat of fusion as noted above. Note that during this transformation, the temperature of the ice-water mixture remains constant even though energy is being added to the mixture.

Once the ice has fully melted, the addition of heat causes the temperature of the water to begin increasing again. The temperature of the pound of water increases by 1°F for every Btu of sensible heat supplied. The amount of heat required to increase the temperature of a pound of a substance 1°F is referred to as that substance's specific heat. The specific heat is water in its liquid state is 1 Btu/lb-°F. Therefore, increasing the temperature of a pound of water in its liquid state from 32°F to 212°F requires 180 Btu of sensible heat.

At 212°F the water begins to boil which results in its change in state from liquid to vapor. As noted above, the latent heat of vaporization for water is 970 Btu/lb and it takes 970 Btu to transform the pound or water from its liquid state to its vapor state. Again note that there is no change in temperature while the water is boiling even though heat is being added to the water-vapor mixture throughout the process.

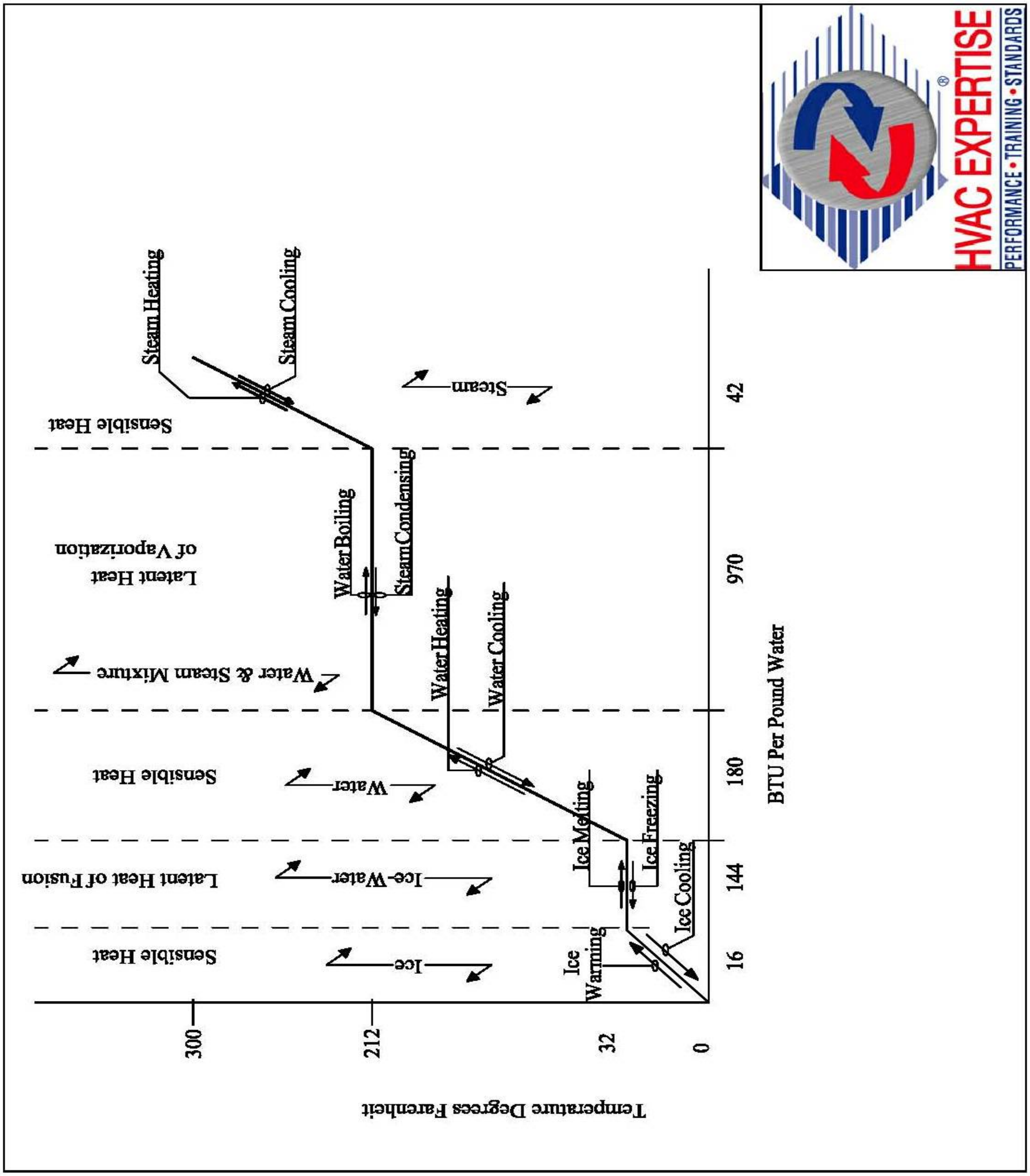
Finally, once all of the liquid water has become vapor the temperature begins to increase again indicating sensible heating. With the addition of another 42 Btu, the pound of water in its vapor state increases in temperature from 212°F to 300°F. Steam heated to a temperature above water's boiling point is referred to as superheated steam.

As noted previously and illustrated in Figure 2-3, the process can be reversed going from steam at 300°F to ice at 0°F.

2.9.5 Total Heat

Total heat or enthalpy is the sum of the sensible and latent heat in an exchange process. In many cases, the addition or subtraction of sensible and latent heat at terminal coils occurs simultaneously. Total heat is also referred to as enthalpy. Both total heat and enthalpy refer to the quantity of energy contained in a substance.

Figure 2-3 Relationship Between Sensible & Latent Heating for Water



2.9.6 Change Of State Terminology

Evaporation. Evaporation is the change of state from liquid to vapor.

For example, evaporative cooling is an adiabatic exchange of heat between air and a water spray or wetted surface. The water approaches the wet-bulb temperature of the air which remains constant during its traverse of the exchanger.

Condensation. Condensation is the process of changing a water vapor into liquid by extracting heat.

In HVAC systems, condensation of steam or water vapor is effected in either steam condensers or dehumidifying coils and the resulting liquid is referred to as condensate.

2.10 AIR CONDITIONING TON

In air conditioning and refrigeration it is very important to understand what a ton of cooling capacity represents because most air conditioning and refrigeration equipment and systems are rated in tons of cooling capacity. A ton of cooling or refrigeration capacity is equivalent to the amount of cooling that would be provided by melting a ton or 2000 pounds of ice over a 24-hour period.

Since the latent heat of fusion required to melting one pound of ice at 32°F is about 144 Btu, one ton of cooling capacity is approximates the following rate of thermal energy transfer in British thermal units per hour:

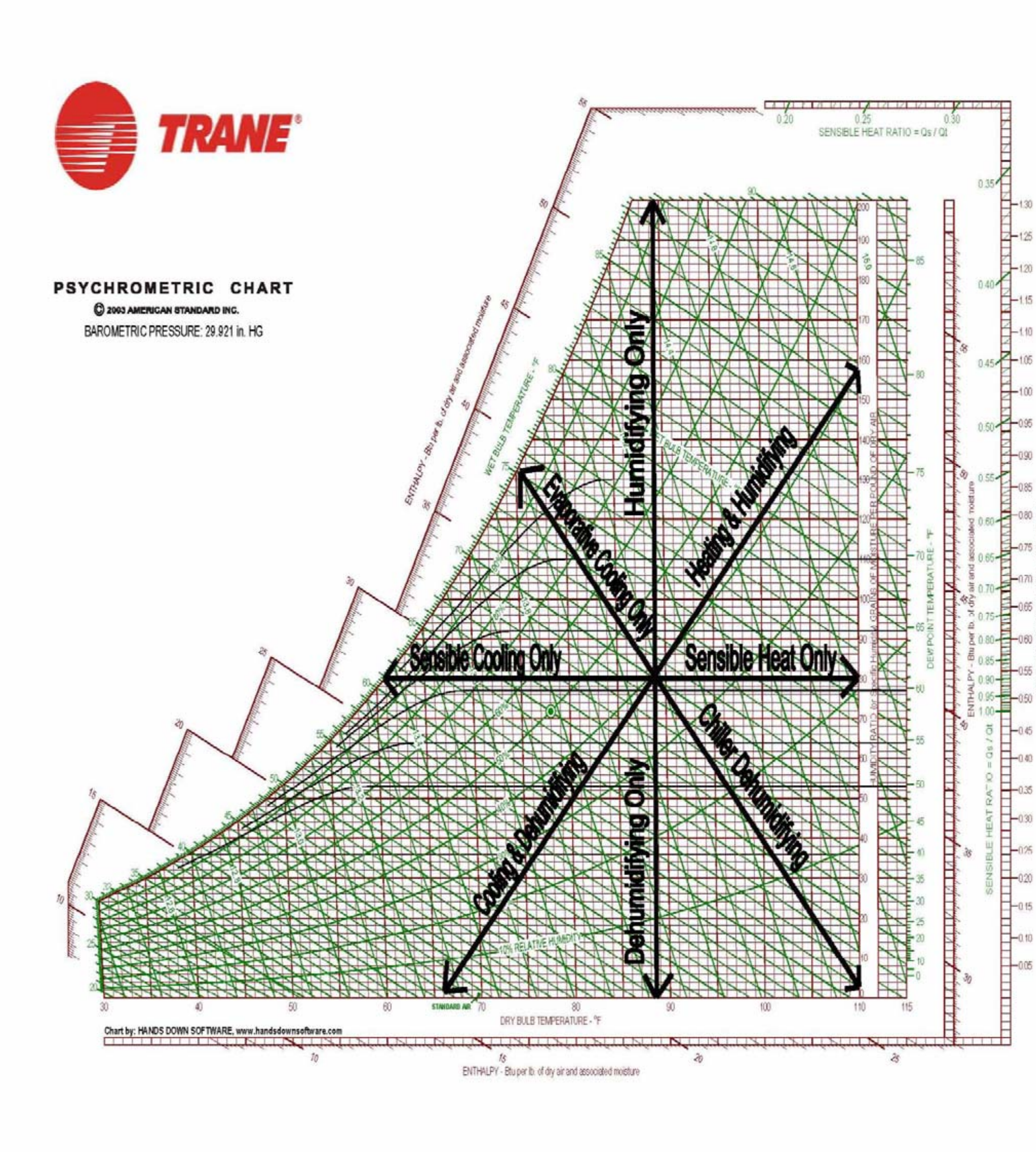
$$\text{One Ton Cooling Or Refigeration Capacity} = \left(\frac{2000\text{ lbs}}{24\text{ hours}}\right)\left(\frac{144\text{ Btu}}{\text{lb}}\right) = 12000\text{ Btu/hr}$$

2.11 SIMPLE SPACE CONDITIONING PROCESSES

Figure 2-4 illustrates the following simple space conditioning processes using a psychrometric chart as discussed in Section 2.6:

- Sensible Cooling
- Sensible Heating
- Humidifying
- Dehumidifying
- Cooling & Dehumidifying
- Heating & Humidifying
- Chemical Dehumidifying
- Evaporative Cooling

Figure 2-4 Simple Space Conditioning Processes (on Psychrometric Chart)



CHAPTER III
HVAC SYSTEM BASICS

3.1 INTRODUCTION

This chapter builds on Chapter II by introducing the basics of HVAC systems. In Chapter II heat transfer, heat transfer mechanisms, heat transfer units, and heat transfer media was covered which is key to understanding HVAC equipment and systems. This chapter begins by defining the purpose of an HVAC system which provides the foundation for the remainder of the chapter. Thermal comfort is then discussed along with the importance of indoor air quality (IAQ) and HVAC energy use. The four basic elements of any HVAC system are presented followed by a discussion of space conditioning methods and HVAC system categories.

3.2 HVAC SYSTEM PURPOSE

The objective of an HVAC system is to provide a suitable thermal environment in a defined space that meets the needs of the occupants, activity that takes place in the space, or both. Most HVAC systems are installed to establish an indoor environment within which building occupants can live, work, and play. The indoor environment impacts the quality of life, productivity, and well being of building occupants. As people spend an increasing amount of time inside buildings, HVAC systems and their associated control systems are becoming more important which is why the focus of this manual is on human comfort. In addition, energy use in buildings is becoming increasingly important and impacting the type of the HVAC system selected, the HVAC equipment used, and how the HVAC operates. HVAC systems are also required to provide suitable environmental conditions for purposes other than or in addition to human comfort. Special purpose HVAC systems are addressed in Chapter XI of this manual.

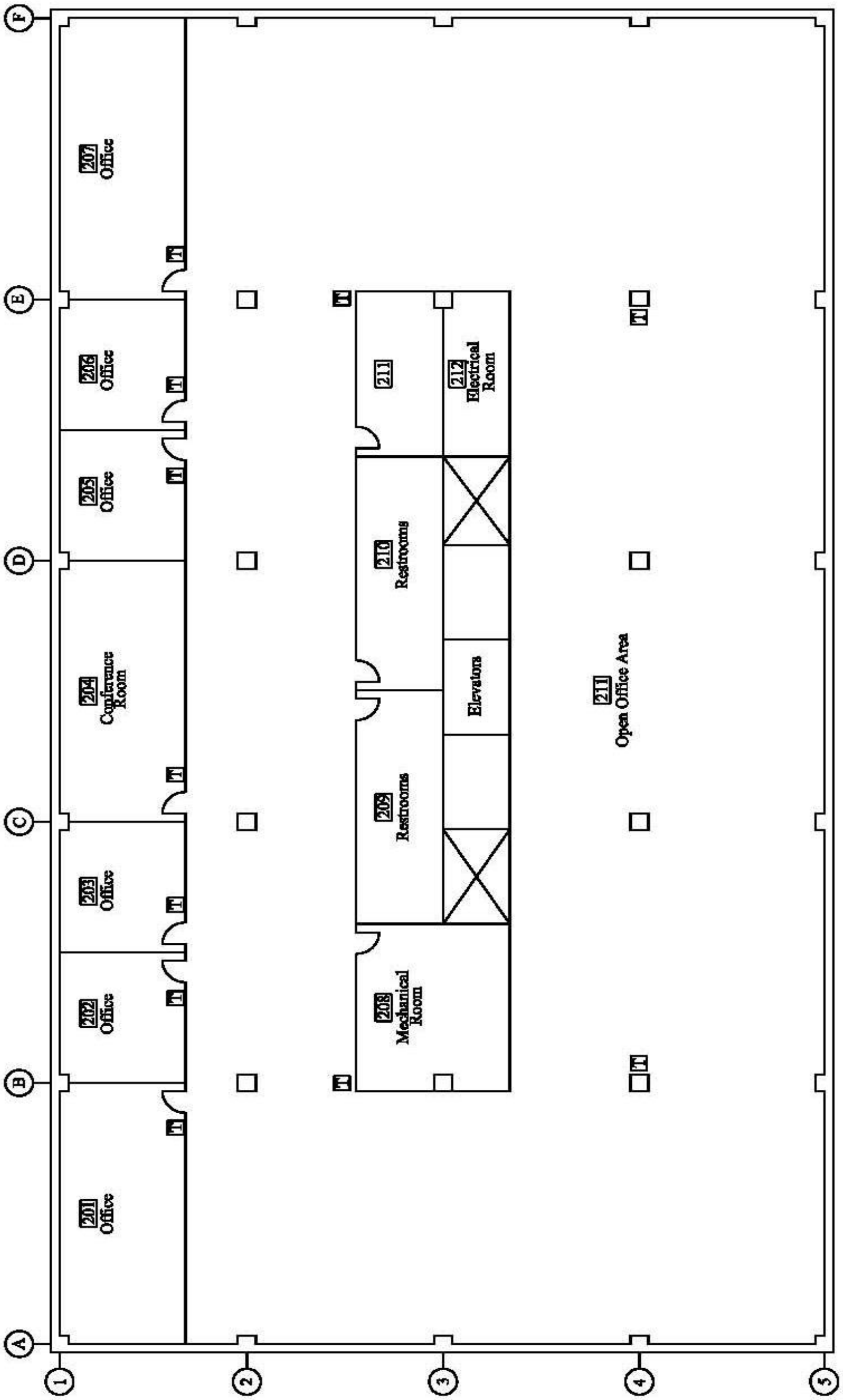
3.3 HVAC ZONES & SPACES

3.3.1 Zone

A “zone” is a designated area of a building that has its own sensors to monitor the thermal conditions in that area and control the HVAC system serving that area. Zoning is not determined by the number of air outlets in a designated area but rather the control of those air outlets. One set of sensors can control multiple air outlets. For example, a single-family residence is typically single zone because there is usually a single thermostat centrally located in the home that controls the HVAC system that serves the entire home.

The floor plan of a commercial office building is shown in Figure 3-1. As can be seen from Figure 3-1, each office (e.g. Room 201) has its own thermostat that monitors and controls the temperature of the office. Similarly the conference room (Room 204) also has its own thermostat making it a zone as well. The open office area is divided into four quadrants that are each monitored and controlled by its own thermostat (e.g. Column B4). As a result, the open office area consists of four zones even though it is a single contiguous space.

Figure 3-1 Commercial Office Building Floor Plan



Typically, the thermal condition in a commercial building zone is controlled by a thermostat that monitors the temperature in the zone and controls the HVAC system serving that zone. This thermostat compares the measured temperature in the zone to its setpoint which is the desired temperature. However, zoning in commercial buildings can include other sensors that track other variables including occupancy and carbon dioxide that work together with the thermostat to provide a comfortable and healthy environment for occupants as well as efficient operation of the HVAC system serving the zone.

3.3.2 Space

A "space" is an area of a building that is defined by walls or other architectural features that restrict free air movement between that area and other parts of the building. A space can be a zone when there is only one set of sensors that monitor and control the thermal conditions in the space. An example of a space that might also be a zone in a commercial building would be the offices or conference room shown in Figure 3-1. Similarly, a large space such as the open office area in Figure 3-1 might include multiple zones where multiple sets of sensors are used to control thermal conditions in different areas within the space.

3.4 AIRFLOW DEFINED

The term "airflow" is used throughout this manual to denote the volumetric rate of air supply through the air distribution system to a zone or space. The volumetric rate of air supply is usually expressed as either cubic feet per minute (cfm) in English units or cubic meters per second (m^3/sec) in metric units.

3.5 FOUR VARIABLES THAT IMPACT HUMAN THERMAL COMFORT

Thermal comfort is determined by the following four variables:

- Temperature
- Humidity
- Air Movement
- Air Quality

These four variables and their impact on human comfort will be discussed in the sections that follow.

3.6 DEFINING HUMAN THERMAL COMFORT

3.6.1 ASHRAE Standard 55

Chapter II covered the properties of moist air and showed that temperature and humidity are linked as shown by the psychrometric chart. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) publishes ASHRAE Standard 55-2004 entitled *Thermal Environmental Conditions for Human Occupancy*. This standard specifies the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80 percent of the occupants in a space. The environmental factors addressed are temperature, thermal radiation, humidity, and air speed. Additionally, personal factors such as the activity being performed in the space and clothing are also covered in this standard.

3.6.2 ASHRAE Summer & Winter Comfort Zones

Comfort zones defined by dry bulb temperature and relative humidity in a space on a psychrometirc chart are defined in ASHRAE Standard 55-2004 for summer and winter as shown in Figure 3-2. As noted above, the comfort zones provide a range of temperature and humidity conditions that will satisfy most people who are appropriately dressed and performing light activity such as office work. People involved in strenuous activity or those wearing heavier clothing may need cooler conditions than the comfort zones shown in Figure 3-2. The summer and winter comfort zones are different because people dress different in each season.

Figure 3-3 plots the ASHRAE summer and winter comfort zones on a full psychrometric chart to provide context to Figure 3-2. From Figure 3-3 it can be seen that the summer and winter comfort zones comprise only a small part of the entire psychrometric chart indicating that a very narrow range of temperature and humidity conditions defines human comfort. Both the winter and summer comfort zones are bounded by a minimum humidity ratio of about 4.5 pounds of water vapor per thousand pounds of dry air in Figure 3-2. A pound of water vapor is equal to 7,000 grains of water vapor so 4.5 pounds of water vapor per thousand pounds of dry air equates to about 32 grains of water vapor per pound of dry air in Figure 3-3.

For the summer comfort zone, the upper bound is defined by the 68^{o}F wet bulb temperature line at the upper bound of humidity which varies from a humidity ratio of 88 grains of water vapor per pound of dry air at 79^{o}F dry bulb to about 98 grains of water vapor per pound of dry air at 73^{o}F dry bulb. Said another way, the upper bound of the summer comfort zone traces the 68^{o}F wet bulb temperature line from about 79^{o}F dry bulb at about 68 percent relative humidity to about 73^{o}F dry bulb at almost 80 percent relative humidity. At the lower bound, the summer comfort zone varies from 76^{o}F dry bulb at about 25 percent relative humidity to about 81^{o}F dry bulb and around 20 percent relative humidity. Within these narrow boundaries of temperature and humidity, any combination of these two variables will result in human comfort.

Figure 3-2 ASHRAE Summer & Winter Comfort Zones

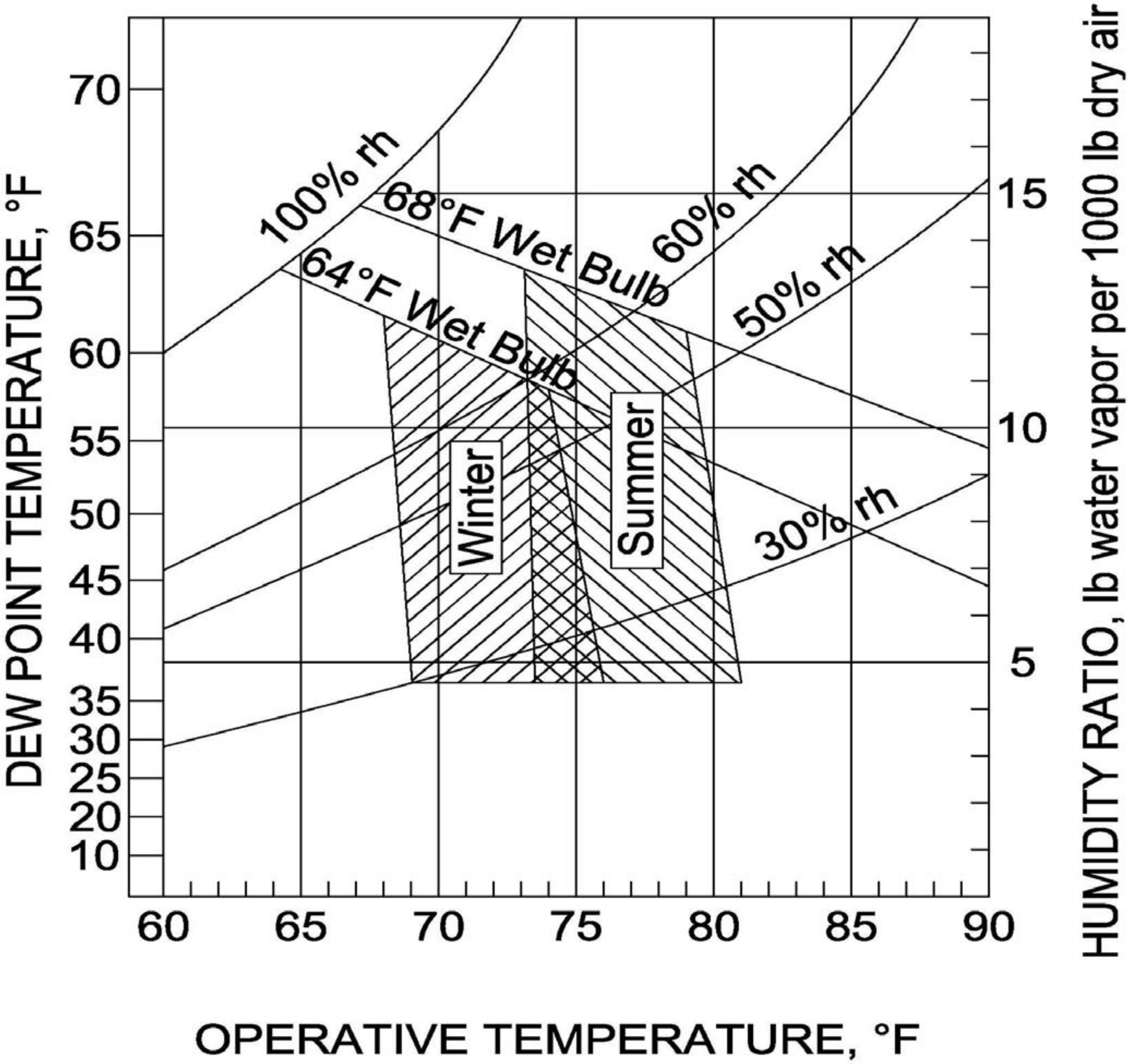
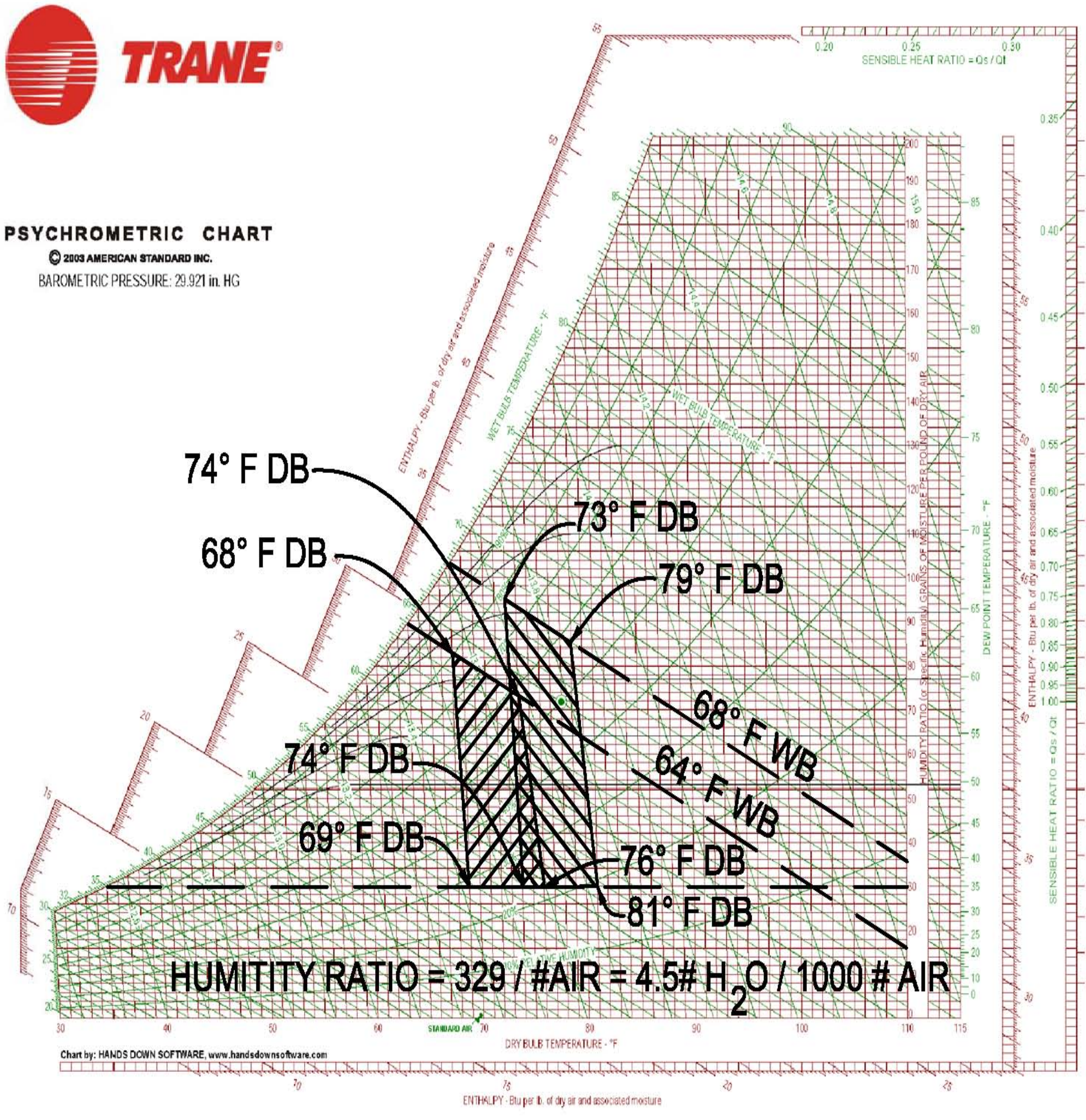


Figure 3-3 ASHRAE Summer & Winter Comfort Zones (on Psychrometric Chart)



A similar analysis can be made of the winter comfort zone and as can be seen from Figure 3-2, temperatures for human comfort are lower in the winter because people wear more and heavier clothes and humidity requirements are also less resulting in the winter comfort zone being shifted to the left of the summer comfort zone.

As can be seen from Figures 3-2 and 3-3, as indoor air temperature varies the humidity also varies. The indoor humidity generally stays within the comfort zone but in dry climates HVAC systems often have a humidifier to increase the moisture level of the conditioned air being supplied to the space when it is needed. In humid climates, HVAC systems may need to include a dehumidifier to remove excess moisture from the air to achieve human comfort.

3.7 INDOOR AIR QUALITY

3.7.1 Importance Of Indoor Air Quality

Indoor air quality (IAQ) is also a very important factor both for human comfort and the safety and health of occupants. Indoor air quality can be contaminated by the presence of all different types of pollutants that are both gaseous and particulate. Gaseous pollutants occur naturally as in the case of carbon dioxide and carbon monoxide. Carbon dioxide enters the indoor atmosphere as a result of simple respiration or breathing by humans and animals occupying the space. Similarly, carbon monoxide is a by product of combustion and can enter the indoor atmosphere as a result of cooking or heating with natural gas or other organic materials such as wood. In addition, the use of chemicals such as paints, adhesives, and pesticides can also pollute the indoor environment and impact occupant comfort due to odors or cause headaches and sickness. Lastly, there are both inanimate and living particulates that are present in the air. These particulates include dust, small insects like mites, molds, bacteria, and viruses.

Today, people spend most of their lives living, working, and playing inside of buildings. As a result, indoor air quality is a very important aspect of any HVAC system and pollutants must either be removed from the air stream as it passes through the HVAC system or must be diluted to acceptable levels by the introduction of outside air to mix with recirculated conditioned air. In the case of gaseous pollutants such as carbon dioxide and carbon monoxide it is very difficult and expensive to remove them from the air stream using chemical air cleaners and gas phase filtration methods. It is typically more effective and economical in commercial and institutional buildings to increase the amount of outside air brought into the building and dilute the concentration of gaseous pollutants like carbon dioxide and carbon monoxide to acceptable levels.

3.7.2 ASHRAE Standard 62.1

Air quality is addressed in ASHRAE Standard 62.1-2004 entitled *Ventilation for Acceptable Indoor Air Quality*. The purpose of this standard is to specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to minimize the potential for adverse health effects. This standard applies to all indoor or enclosed spaces that people may occupy. This standard considers the chemical, physical, and biological contaminants that can affect air quality. Thermal comfort requirements are not included in this standard because they are addressed in ASHRAE Standard 55.

3.8 HVAC SYSTEM ENERGY USE

3.8.1 HVAC System Energy Use

Buildings account for about 48 percent of the U.S. energy consumption and generate more greenhouse gas than any other sector. The U.S. Department of Energy (DOE) estimates that space heating, space cooling, and water heating account for about 43 percent of a commercial or institutional building's energy use as shown in Figure 3-4. The American Institute of Architects (AIA) has set a goal of carbon-neutral buildings by 2020 as part of their "2030 Challenge." Similarly, ASHRAE has plans to create a "Net Zero" guide for building design and construction by 2020. DOE's Building Technologies Program has set a goal of "zero energy buildings" by 2025. This movement toward zero energy buildings (ZEBs) in response to concerns about the environment and energy is translating into the need for high-performance HVAC systems for commercial and institutional buildings that significantly reduce energy use while simultaneously maintaining human comfort and a healthy indoor environment.

3.8.2 ASHRAE/IESNA Standard 90.1

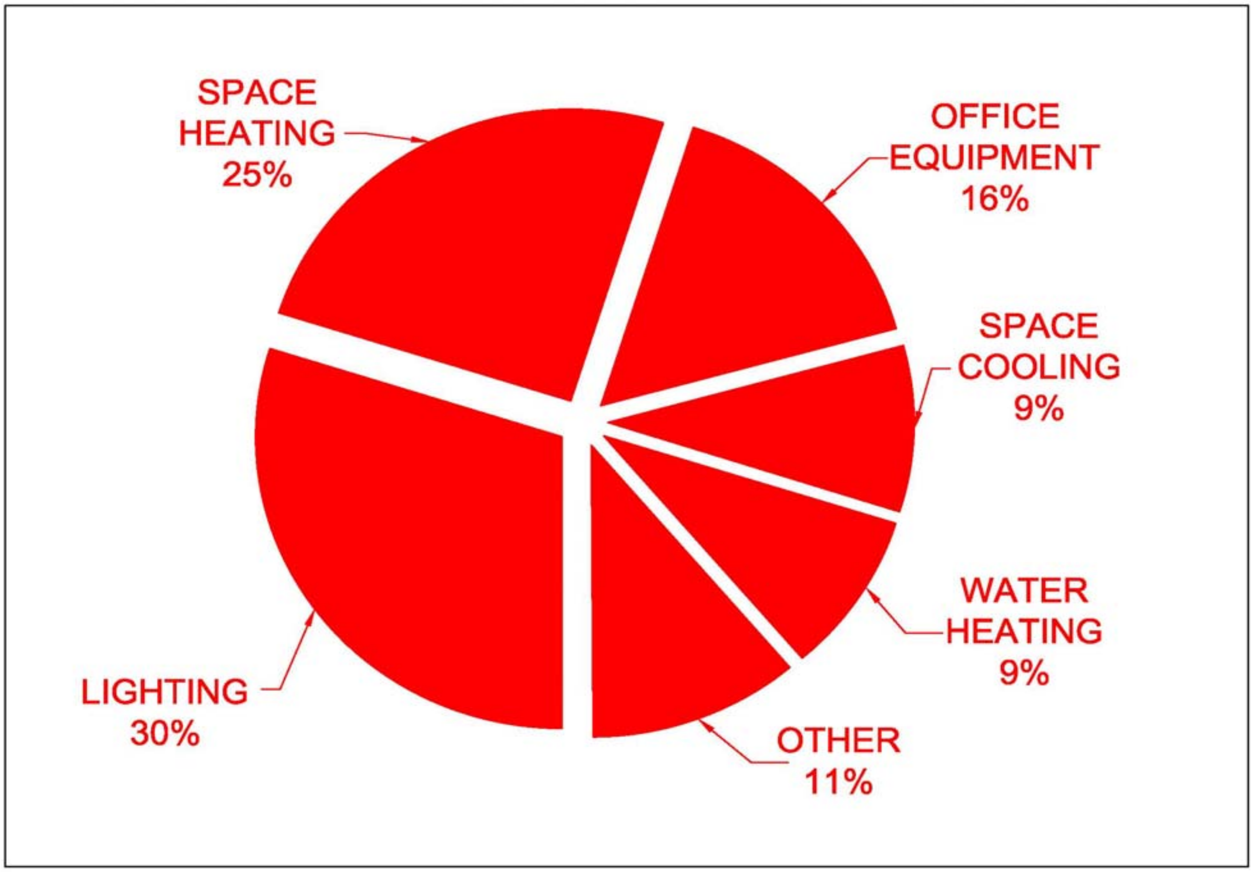
ASHRAE publishes ASHRAE/IESNA Standard 90.1-2007 entitled *Energy Standard for Buildings Except Low-Rise Residential Buildings* in conjunction with the Illuminating Engineering Society of North America (IESNA). The purpose of this standard is to provide the minimum requirements for the energy-efficent design of buildings. AHRAE/IESNA Standard 90.1 covers new buildings as well as building expansions and renovations and specifically addresses not only the building envelope and its thermal properties but also HVAC equipment, water heating, and electric motors which are all part of a commercial or industrial building's HVAC system. This standard provides both prescriptive and performance requirements for HVAC system operation and has been adopted directly as a requirement by federal, state, and local governments and agencies as well as incorporated into building and energy codes.

Third-party green building rating systems such as the U. S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED^{TM}) and the Green Building Initiative's (GBI) Green Globes^{TM} rating systems have adopted ASHRAE/IESNA 90.1 as a minimum requirement for certification as a green building. To achieve additional credits toward certification or a higher certification, the HVAC systems must outperform the minimum ASHRAE/IESNA 90.1 requirements. Many public and private owners today want their buildings certified as a green building by a third-party rating system like those sponsored by the USGBC and GBI which makes this standard a very important standard for the HVAC industry.

3.8.3 International Energy Conservation Code

The *International Energy Conservation Code* (IECC) is published by the International Code Council (ICC) as part of its family of building codes. Like AHRAE/IESNA Standard 90.1, the IECC establishes minimum prescriptive and performance-based requirements for the design of energy-efficient buildings.

Figure 3-4 Commercial & Institutional Building Energy Use



3.8.4 Other Energy Codes & Standards

In addition to those codes and standards discussed in this section, there are a myriad of other building and energy codes and standards promulgated by federal, state, and local governments as well as other industry organizations. One example is *Title 24, Part 6 of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings* which were established in 1978 in response to a legislative mandate to reduce California's energy consumption. As concern about the environment and energy use increases, energy codes and standards will become increasingly important and have a greater impact on HVAC system design, installation, and operation.

3.9 HVAC SYSTEM OPERATION

HVAC systems provide a comfortable thermal environment for occupants through heat and moisture transfer via the following three mechanisms:

- Supply and mixing of air in a zone.
- Direct heat transfer with the air in a zone.
- Supply of outside air for indoor air quality (IAQ).

3.10 BASIC HVAC SYSTEM MECHANICAL ELEMENTS

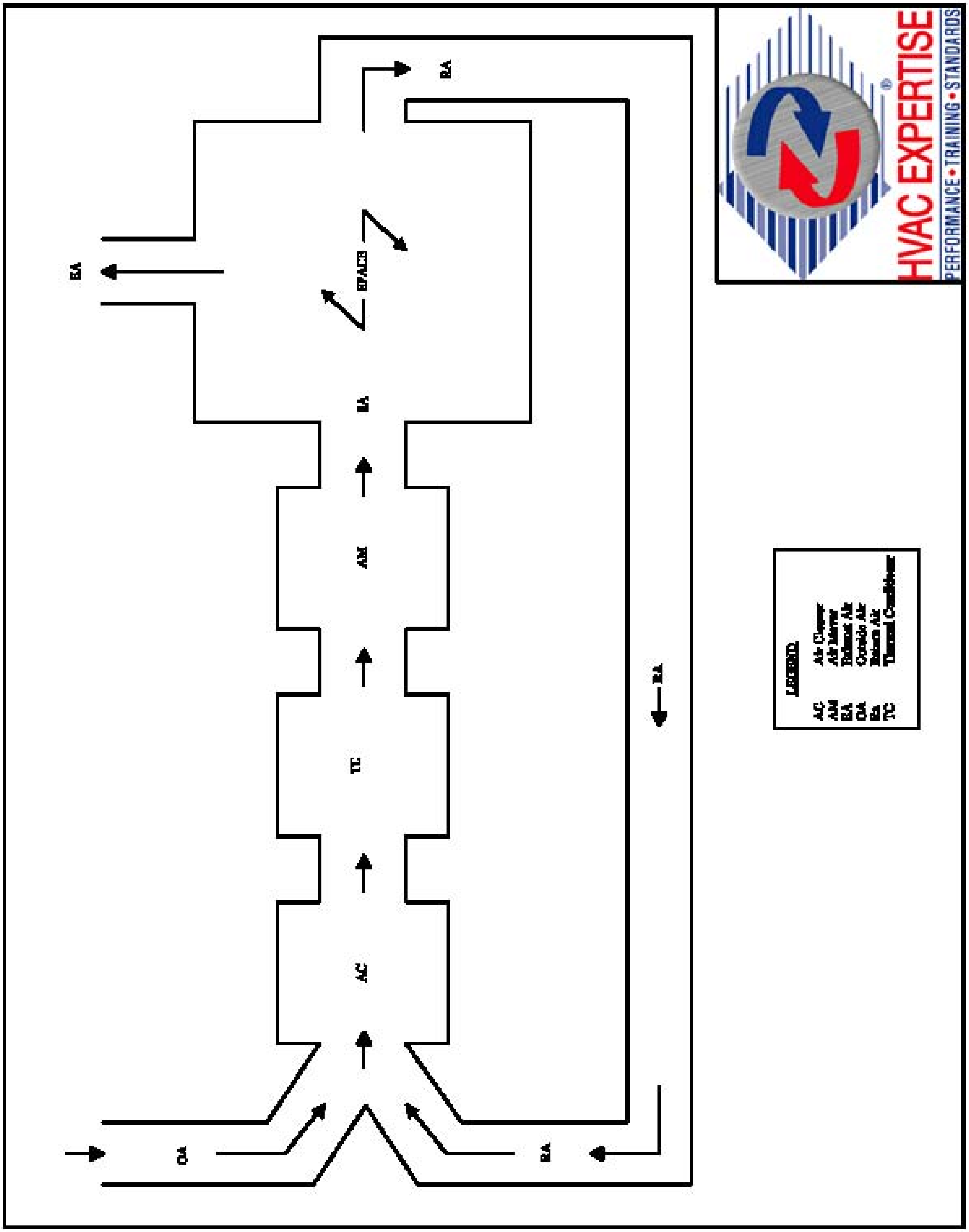
3.10.1 Basic HVAC System Mechanical Elements

As noted previously, the purpose of any commercial or institutional HVAC system is to provide thermal comfort and a healthy environment for building occupants by controlling the building's temperature, humidity, air movement, and air quality. Figure 3-5 provides a simplified block diagram of an HVAC system that is intended to provide a comfortable and healthy thermal environment for zone occupants by controlling the four thermal comfort variables. The four basic building blocks of this basic HVAC system are as follows:

- Air Cleaner
- Thermal Conditioner
- Air Mover
- Air Distribution System

These four basic building blocks are found in any HVAC system regardless of the size or complexity. A self-contained HVAC unit such as a common residential window air conditioner needs all four of these building blocks as much as a large commercial or institutional HVAC system that includes a central heating and cooling plant, extensive air and hydronic distribution systems, and air handling units located in mechanical equipment rooms throughout the building. The following paragraphs will discuss each of these four basic building blocks.

Figure 3-5 Basic HVAC System Elements



3.10.2 Air Cleaner

Whether contaminants are in the outside air brought into the building or introduced in the building itself, they can impact the comfort and health of building occupants. These constituents are often referred to as contaminants or pollutants that need to be removed from the air stream or have their concentration reduced to where they are both harmless and unnoticeable to occupants. These contaminants can either be gaseous or particulate.

Gaseous pollutants are either naturally occurring as in the case of carbon dioxide or carbon monoxide or they the byproducts of combustion, chemicals that are used in the building, or off gassed from building materials and furnishings. Gaseous pollutants that result from combustion can include gas cooking and vehicle exhaust. The use of materials such as adhesives, paints, cleaning products, and pesticides can also result in gaseous pollutants. Gaseous pollutants are most often dealt with by mixing outside air with recycled inside air to reduce the concentration of these gases in the building because gaseous pollutants are often difficult and expensive to filter out. However, gas-phase air filtration systems can be used to remove certain gaseous pollutants.

Besides gases, both outside and recirculated inside air usually has both inanimate and living particulates suspended in it that need to be removed or have their concentration reduced. Particulate contaminants include dust, smoke, and pollen ass well as living particulate such as dust mites, molds, bacteria, and viruses. The purpose of the air cleaner in this case is to remove particulate pollutants from the air stream and the building by filtering them out as they pass through the HVAC system. Air cleaners used to remove particulate pollutants include mechanical air filters and electronic air filters that trap particulates as they pass through. In the case of living organisms it is often better to destroy them instead of just trapping them in a filter. This can be accomplished by particulate destruction systems such as ultraviolet germicidal irradiation (UVGI) systems that use ultraviolet light.

3.10.3 Thermal Conditioner

After passing through the air cleaner in Figure 3-5, the air stream then passes through the thermal conditioner. The purpose of the thermal conditioner is to condition the incoming air by altering the incoming air's temperature and humidity so that it is suitable for distribution and delivery to the zone or zones served. The thermal conditioner may be capable of adding heat, removing heat, or both using heat exchangers. For heating, the temperature of the air can be increased by passing it through a hot water or steam heat exchanger that transfers thermal energy to the air and increases its temperature. Heating can also be accomplished using an electric resistance heating or other means. Similarly, the incoming air can be cooled by removing heat energy from it by passing it through a chilled water or refrigerant heat exchanger.

Humidity control can be accomplished using humidity control equipment such as humidifiers and dehumidifiers for defined spaces and special occupancies like indoor pools and ice rinks. However, humidification and dehumidification can also be accomplished introducing water into the air stream in the thermal conditioner or removing it by lowering the temperature and condensing the water out before reheating it to the desired temperature.

The thermal conditioner for a commercial or institutional HVAC system can be either an all-in-one package as in the case of unitary HVAC equipment or distributed throughout the building with a central heating and cooling plant and local air handling units or convection terminal units serving designated building zones.

3.10.4 Air Mover

An air mover is required to pull the air through the air cleaner and thermal conditioner as well as push the air through the air distribution system at the right airflow to the zone or zones served by the HVAC system. Air movement is also one of the four variables that determine thermal comfort. In HVAC systems, the air mover is a mechanical fan which can be either an axial or centrifugal fan. For ducted air distribution systems, fans are typically either a backward curved blade centrifugal fan or a vane-axial fan because of the static pressure. For other HVAC applications, other types of fans are used whose characteristics best match the application. For example, propeller fans are often used for exhaust purposes because there is little static pressure at the discharge and they are very efficient and inexpensive.

3.10.5 Air Distribution System

The purpose of the air distribution system is to deliver air to the zone served by the HVAC system, mix the supply air with the existing air in the zone to achieve the desired temperature without drafts or stratification, and extract and return the existing air in the zone for mixing with new outside air and reconditioning or exhaust to the outside. As can be seen from Figure 3-5, outside air is mixed with return air from the zone and this mixture flows through the air cleaner, thermal conditioner, and air mover where it is conditioned and then delivered to the zone as supply air via the supply air duct. The supply air is mixed with the existing air in the space and then either exhausted to the outside, recirculated through the return air duct to be reconditioned, or a combination of both. The air distribution system consists of ducts and plenums along with duct accessories and air outlets and inlets. Duct accessories include dampers, turning vanes, and silencers. Air outlets and inlets include diffusers, grilles, and registers.

3.11 HVAC CONTROLS

The simplified block diagram provided in Figure 3-5 would be fine if the thermal conditions inside and outside the building were fixed and did not change. However, the thermal environment both inside and outside the building is constantly changing and for the HVAC system to be effective it must be dynamic and capable of automatically adapting to these changing conditions. Inside the building, the demands on the HVAC system are continuously changing with changes in the number of people, the activity taking place, the equipment operating, and other factors. The outside environment is also in a constant state of flux that requires the HVAC system to adapt to the season which includes the effects of both outside temperature, wind, and solar radiation; everyday outside weather changes; time of day; and other factors.

In addition to the mechanical elements discussed in the previous section and illustrated in Figure 3-5, the HVAC system must have a control system that is capable of gathering data on inside and outside environmental conditions as well as the current HVAC system operation, processing this data, and directing changes to the system operation based on this data. The HVAC control system is not only key to the effective operation of the HVAC system equally important to ensuring the efficient operation of the HVAC system.

3.12 SPACE CONDITIONING METHODS USED BY HVAC SYSTEMS

3.12.1 Space Conditioning Methods

An HVAC system conditions a space by introducing air with the needed combination of temperature and humidity into the zone to mix with existing air to ensure that the thermal conditions in the space are within the thermal comfort zone. In addition, sufficient outside air needs to be supplied to the space to ensure indoor air quality. The effectiveness of the HVAC system depends on the following two factors:

- The airflow supplied to the zone.
- The temperature and humidity of the air being supplied to the zone.

To heat or cool a space, these two factors are combined in different ways depending on the type of HVAC system installed. HVAC systems are often classified by how these two factors are combined to condition a zone as follows:

- Constant Air Volume – Variable Air Temperature (CAV-VAT)
- Variable Air Volume – Constant Air Temperature (VAV-CAT)
- Variable Air Volume – Variable Air Temperature (VAV-VAT)

All HVAC systems can be categorized as one of these three systems.

3.12.2 Constant Air Volume – Variable Air Temperature

A constant air volume-variable air temperature (CAV-VAT) HVAC system supplies conditioned air to the HVAC zone that it serves at a constant airflow. The temperature in the zone is controlled by a CAV-VAT HVAC system by varying the temperature of the air supplied to the space. To cool the zone in response to an increase in the thermal load, cooler supply air is delivered by the CAV-VAT HVAC system at constant airflow to mix with the existing air in the zone and lower the temperature. Similarly, when the zone requires less cooling because the thermal load has decreased, the CAV-VAT HVAC system delivers warmer air at a constant airflow to increase the temperature of the zone.

CAV-VAT HVAC systems were the first type of systems that were used in commercial and institutional buildings for cooling. CAV-VAT systems are still being used in existing buildings but these systems are often being converted to or replaced by the more efficient variable air volume-constant air temperature (VAV-CAT) systems that will be discussed next. Additionally, the more efficient VAV-CAT systems are supplanting CAV-VAT systems in most new construction today.

3.12.3 Variable Air Volume – Constant Air Temperature

A VAV-CAT HVAC system works just the opposite of a CAV-VAT HVAC system to condition the zone served. With a VAV-CAT HVAC system, the temperature of the supply air remains constant and the airflow is varied. When cooling is required because the thermal load in the zone increases, a VAV-CAT cooling system delvers an increased airflow to the zone at a constant temperature. The increased conditioned air delivered to the zone mixes with the existing higher temperature air and the zones temperature decreases to the desired value. Similarly, if the thermal load in a zone served by a VAV-CAT HVAC system decreases, the amount of conditioned air delivered to the zone is reduced allowing the zone's temperature to increase to the desired value. As noted above, VAV-CAT systems are more efficient that CAV-VAT systems. As a result, almost all HVAC systems installed in commercial and institutional buildings are VAV-CAT HVAC systems.

3.12.4 Variable Air Volume – Variable Air Temperature

A third method of maintaining the desired temperature in an HVAC zone would be to use a variable air volume-variable air temperature (VAV-VAT) system where both the airflow and temperature of the conditioned air delivered to the space is varied. While this is a possibility, HVAC systems for commercial and institutional buildings are not designed, installed, or operated as VAV-VAT systems. However, it could be argued that many HVAC systems that are classified as either CAV-VAT or VAV-CAT systems are actually VAV-VAT systems. Examples of this might include a terminal unit in a hotel room that is usually considered a CAT-VAV system but has a multi-speed fan whose speed can be manually adjusted by the occupant while the temperature of the air supply is also varied by the operation of the unit. Similarly, a VAV system with reheat that would be classified as a VAV-CAT system actually varies the temperature of the air supplied by the reheat coil in the VAV box as well as the airflow. Therefore, the classification of an HVAC system based on whether airflow, temperature, or both are varied is usually based on its dominant mode of operation which is typically either as a CAV-VAT or VAV-CAT system

3.13 HVAC SYSTEMS CATEGORIZED BY PRIMARY HEAT TRANSFER MEDIA

3.13.1 HVAC System Categorized By Primary Heat Transfer Media

One way to categorize HVAC systems is by the primary heat transfer media that is used to remove or ad heat to the air stream delivered to the HVAC zone. HVAC systems can be categorized using primary heat transfer media as follows:

- All-Air HVAC Systems
- Air-Hydronic HVAC Systems
- All-Hydronic HVAC Systems
- Direct Refrigerant HVAC Systems
- Hybrid HVAC Systems

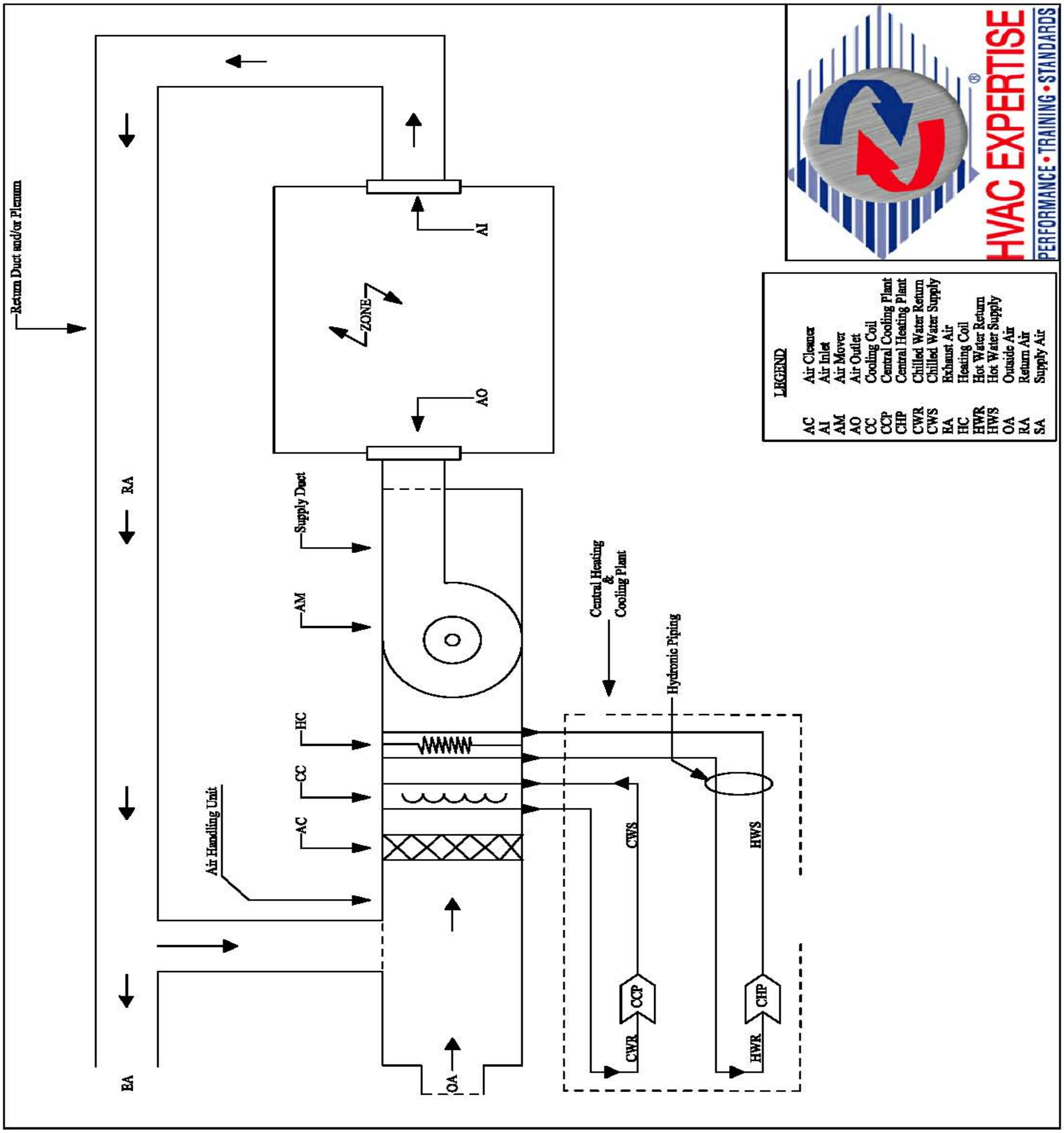
The following paragraphs will discuss each of these HVAC system classifications.

3.13.2 All-Air HVAC Systems

All-air HVAC systems use air as the primary heat transfer medium. Figure 3-6 provides a schematic diagram of an all-air HVAC system that includes all four basic HVAC elements discussed previously and illustrated in Figure 3-6. A mixture or return air from the zone and outside air is conditioned by the air-handling unit and supplied to the zone. The air-handling unit cleans the air and then either cools or heats it using water-to-air heat exchangers shown as the cooling and heating coil, respectively. Air is forced to through the system by the supply fan in the air-handling unit which is the air mover. Conditioned air is then supplied to one of more zones served by the air-handling unit through a supply duct and an air inlet. Return air leaves the room through an air outlet and is routed back through a return duct, plenum or a combination of the two. A portion of the return air is recirculated through the air-handling unit and the remainder is exhausted depending on the zone thermal load, outside air temperature, and need for outside air for air quality.

In the schematic diagram of the all-air HVAC system illustrated in Figure 3-6, heat is added or removed from the air stream by the heating and cooling coils in the air-handling unit. The heating coil uses either hot water or steam supplied from a central heating plant which would typically be a boiler plant and the cooling coil is supplied by chilled water from a central cooling plant which would typically be a chiller plant. The central heating plant is represented by a single box in the in Figure 3-4 but is comprised of boilers, boiler feed pumps, hot water or steam circulating pumps and other mechanical equipment. Similarly, the central cooling plant block in the schematic diagram includes chillers, cooling towers, chilled water circulating pumps and other mechanical equipment. The supply and return of the hot water or stream and the chilled water is accomplished using a hydronic piping system.

Figure 3-6 All-Air HVAC System



Adding or removing heat from the air-stream using water-to-air heat exchangers and either hot water or steam and chilled water generated by a central plant and transported to the air-handling unit using a hydronic piping system is only one way that an all-air HVAC system can operate. To cool the air stream, the air-handling unit could have its own refrigeration unit associated with it and instead of a water-to-air heat exchanger have a direct refrigerant-to-air heat exchanger eliminating the need for chilled water and the central cooling plant. Similarly, heat can be added to the air stream by a variety of methods such as electric resistance heating or direct gas-fired heating. A common example of a standalone all-air HVAC system would be a rooftop packaged HVAC unit which is also categorized as a unitary system.

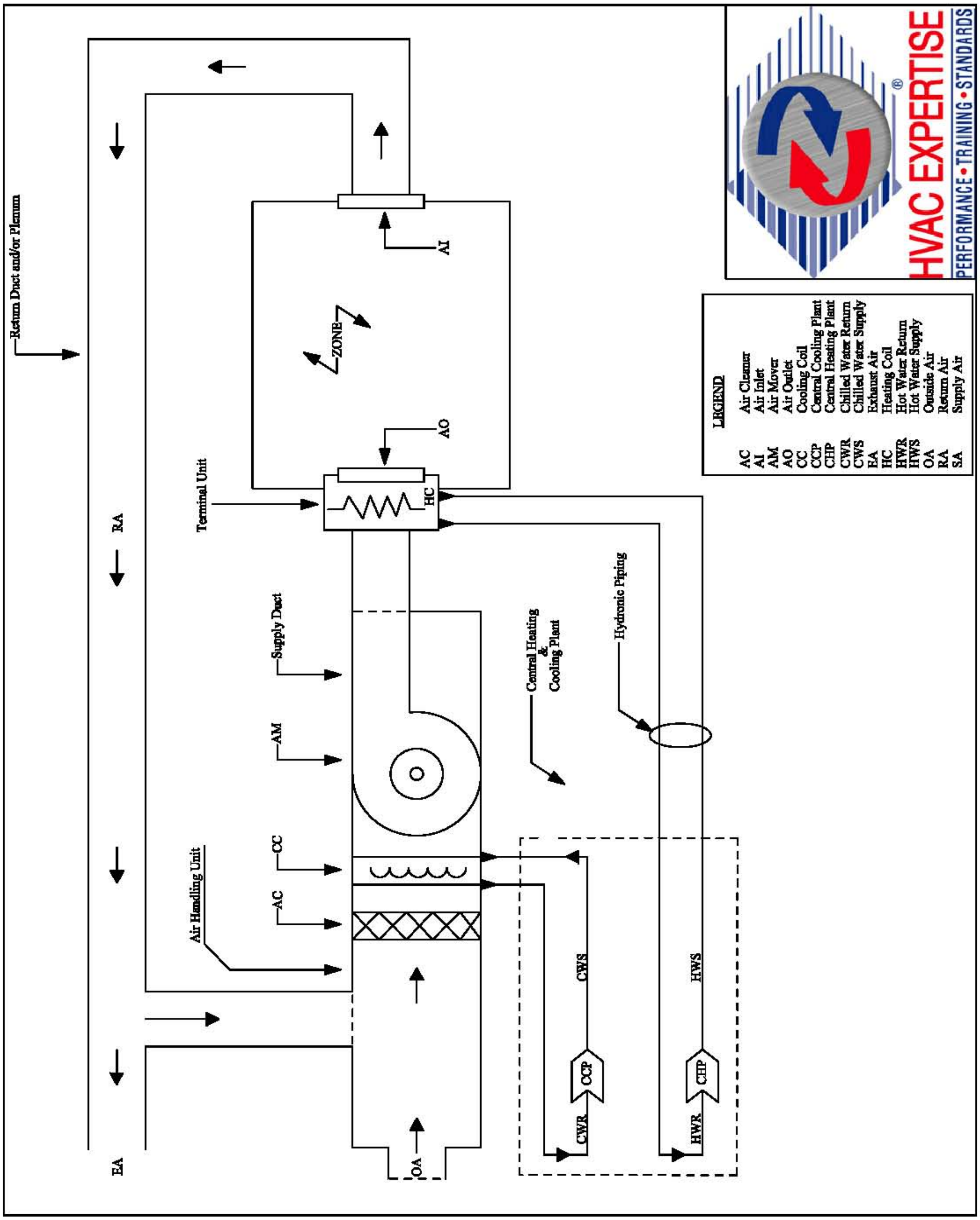
The schematic diagram of the HVAC system in Figure 3-6 also shows both a cooling coil for removing heat from the air stream and a heating coil for adding heat to the air stream. Depending on the building HVAC needs, climate where the building is located, and HVAC system design, both a cooling function and heating function may not be required. The all-air HVAC system may only be required to provide cooling and only need a cooling coil. On the other hand, the all-air HVAC system may be heating-only and only need a heating coil. Also, Figure 3-6 is intended to illustrate the basic layout and function of an all-air HVAC and a number of important components that might be needed to make the system work in a given application such as dampers and return air fans have been omitted to focus on the base system. These additional components will be added and discussed in later chapters of this manual.

3.13.3 Air-Hydronic HVAC Systems

A schematic diagram of an air-hydronic HVAC system is provided in Figure 3-7. As can be seen from Figure 3-7, an air-hydronic HVAC system uses both air and water as the HVAC system's primary heat transfer media. The air stream is filtered and conditioned in the air-handling unit and then supplied to the space through a water-to-air heat exchanger. In this simple air-hydronic HVAC system, the air is cooled in the air handling unit by a water-to-air heat exchanger but this could as easily been a refrigerant-to-air heat exchanger as discussed in the previous section. When heat is required, the cooling coil can be shut down and the air stream supplied by the air-handling unit could be heated by the water-to-air heat exchanger in the zone's terminal unit.

While the zone's terminal unit is shown as a water-to-air heat exchanger in Figure 3-7, it could just as well be an electric resistance heater as discussed in the previous section. Similarly, the air-hydronic HVAC system shown in Figure 3-7 uses an induction unit where the supply air passes directly through the hydronic heating coil before being supplied to the zone. Other air-hydronic systems may not pass the supply air through the terminal unit but instead deliver it directly to the space as in the case with an all-air HVAC system. The zone's heating needs would then be met by radiators, finned tube radiation heaters, and other similar water-air heat exchangers with hydronic piping.

Figure 3-7 Air-Hydronic HVAC



3.13.4 All-Hydronic Systems

A schematic diagram of an all-hydronic system using a local fan coil unit to provide conditioned air to the zone is shown in Figure 3-8. In this case, the fan coil unit is dedicated to the zone and includes an air cleaner along with water-to-air heat exchangers for the cooling coil and the heating coil. The supply air is provided directly to the zone and there is no supply air duct system unlike the all-air and air-hydronic HVAC systems. A return air system is shown in Figure 3-8 but this is typically accomplished by recirculating air from the zone through the unit itself and mixing the recirculated air with outside air in the fan coil unit itself.

As can be seen from Figure 3-8, an all-hydronic HVAC system eliminates the need for an air distribution system and instead uses water as the sole heat transfer media requiring a hydronic distribution system instead. Also, if either heating or cooling is not required then those coils and their associated central plant and distribution system can be eliminated.

3.13.5 Direct Refrigerant HVAC Systems

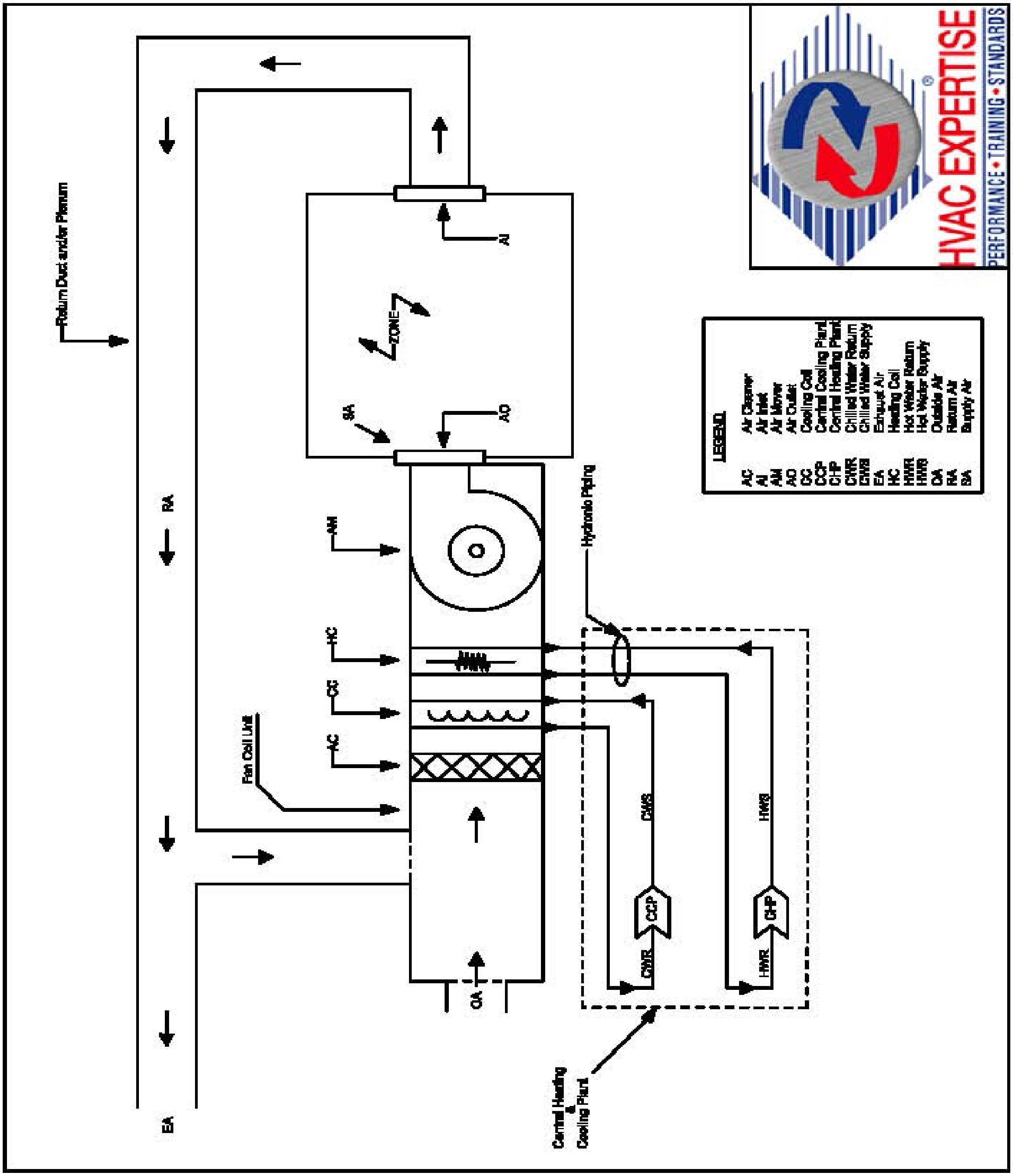
Direct refrigerant HVAC systems eliminate the need for air and hydronic distribution systems because these HVAC units are self contained and intended to serve the zone in which they are located. Direct refrigerant systems are typically cooling only but they can also provide a heating function by reversing the refrigerant cycle or including electric resistance heating. These self-contained HVAC systems are typically referred to as unitary HVAC systems.

An example of a direct refrigerant HVAC system would be a common window air conditioner or a through-wall HVAC unit that is often used in hotels, motels, and apartment buildings that have a number of rooms that are each independent zones and are located on an outside wall of the building. Other applications of direct refrigerant HVAC units are when there is a particular zone such as a data processing or telecommunications room that needs additional cooling. This room can either be located on an outside wall to permit the rejection of heat directly to the outside or use a split system using refrigerant piping to interconnect the supply fan and cooling coil inside with the condenser and compressor outside on the ground or roof.

3.13.6 Hybrid HVAC Systems

Commercial and institutional buildings often use a combination of these basic systems to provide an HVAC system to provide a comfortable and healthy environment for occupants as well as minimize HVAC system life-cycle cost. This is accomplished by utilizing systems based on their advantages for particular applications in buildings. For instance, an all-air HVAC system may be used to cool the interior of an office building while a an air-hydronic HVAC system might be used to provide both cooling and heating to the perimeter of the building which has the highest heat gain in the summer and the highest heat loss in the winter.

Figure 3-8 All-Hydronic HVAC System



3.14 HVAC SYSTEM SPACE CONDITIONING METHODS & CATEGORIES

In general, any of the space conditioning methods can be designed and installed as any of the system categories. However, all-air, air-hydronic, and all-hydronic HVAC systems usually condition a zone using either CAV-VAT or VAV-CAT as shown in the following table:

SYSTEM CATEGORY	**ZONE CONDITIONING METHOD**		
	CAV-VAT	**VAV-CAT**	**VAV-VAT**
All-Air	X	X	
Air-Hydronic	X	X	
All-Hydronic	X	X	
Unitary	X		X

Historically, most HVAC systems were CAV-VAT systems. However, over time VAV-CAT systems have become the systems of choice because properly designed, installed, and operated VAV-CAT systems provide greater thermal comfort for occupants and are more energy efficient than CAV-VAT systems. CAV-VAT systems are still used in older buildings and also in applications where constant airflow is required.

Unitary or standalone HVAC systems such as roof top HVAC units are the only system category that occasionally operates as a VAV-VAT system by varying both the airflow and temperature of the air supplied to the space. This is often accomplished by supplying the unitary unit with both a fan control and temperature control on the unit.

3.15 HVAC SYSTEM EQUIPMENT LOCATION & HEAT TRANSPORT

As in the previous section, there are no hard and fast rules regarding equipment location, heat transport method, and primary heat transfer medium. However, the following table attempts to provide the typical equipment location, piping system, and air distribution system for the four system categories discussed in this chapter.

SYSTEM CATEGORY	**EQUIPMENT LOCATION**	**PIPING SYSTEM**		**AIR DISTRIBUTION SYSTEM**
		HYDRONIC	**REFRIGERANT**	
All-Air	Central			**X**
Air-Hydronic	Central	**X**		**X**
All-Hydronic	Central	**X**		
Unitary	Distributed		**X**	

As can be see from the table and discussed earlier in this chapter, an all-air HVAC system usually has equipment located in a central location, uses air as its primary heat transfer medium, and requires an air distribution system. The primary drawbacks of an all-air HVAC system is the need for an extensive air distribution system which can take up considerable building space if large volumes of air need to be moved from remote locations. Also, air is not as efficient at transferring heat as water that impacts all-air HVAC system efficiency when serving remote building zones. An all-air HVAC system works best when it is serving a small building such as a single-family residence or small commercial building or when it is dedicated to local zones in a larger commercial or institutional building.

Air-hydronic HVAC systems typically use centrally located HVAC equipment and require both hydronic and air distribution systems. The air portion of an air-hydronic HVAC system typically provides cooling and ventilation and the hydronic portion provides heating. The heating is accomplished using water-to-air heat exchangers either located in the air stream to heat the air before delivering it to the zones served or use water-to-air heat exchangers such as radiators located in the zones served.

All-hydronic HVAC systems require only a hydronic piping system that has conditioned water supplied to water-to-air heat exchangers in the zones served. Hot water is supplied for heating and cold water is supplied for cooling. Water-to-air heat exchangers are typically located along an outside wall that allows them to take in all or a portion of outside air for ventilation. A wall mounted fan-coil unit would be an example of a water-to-air heat exchanger in an all-hydronic HVAC system.

Unitary HVAC systems are typically distributed and located in or near the zone that they serve. Unitary HVAC systems are self contained so they don’t need either an air or hydronic distribution system. They are self-contained units whose primary heat transfer media is refrigerant. Often the refrigerant piping is fully contained in the unit as in the case of packaged air conditioning systems that are often installed as rooftop HVAC units. However, there are also split systems where but split systems where the evaporator and supply fan are located indoors and the air-cooled condenser and compressor are located outdoors with refrigerant piping interconnecting them. One of the restrictions associated with split systems is that the distance between the inside and outside units is limited due to the need to keep the refrigerant piping as short as possible.

CHAPTER IV
UNITARY HVAC SYSTEMS

4.1 INTRODUCTION

This chapter covers unitary HVAC systems. Unitary HVAC systems include a wide variety of different types of air-conditioning units that include their own integral refrigeration cycle and range from residential window air conditioning units to rooftop units used for commercial and light industrial applications. In addition to general HVAC applications, unitary HVAC units also include HVAC units for special occupancies and applications such as computer rooms, health care applications, and classrooms.

4.2 UNITARY HVAC SYSTEM CHARACTERISTICS & USE

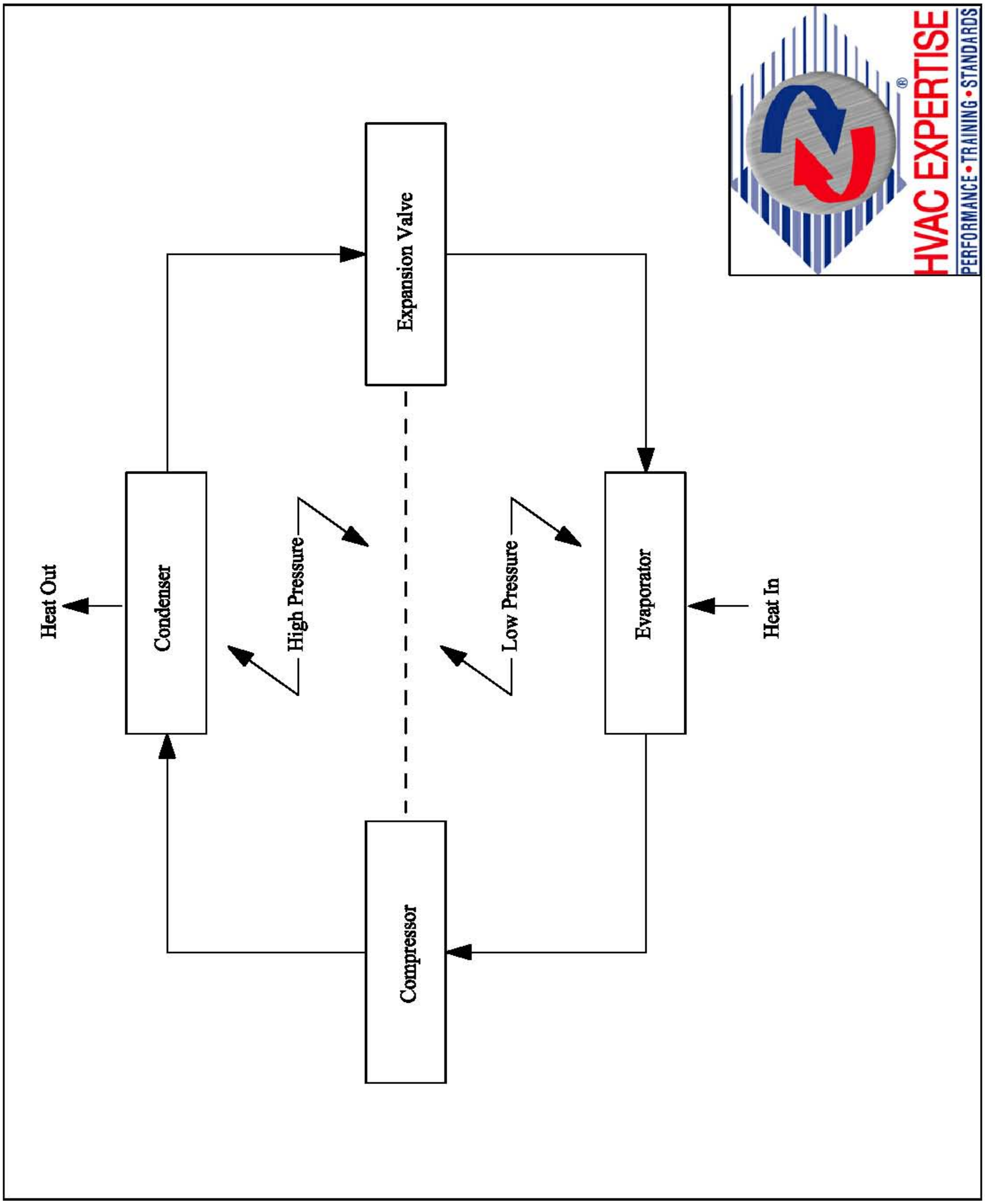
Unitary HVAC systems are also referred to as packaged air-conditioning systems. These systems are typically manufactured as a complete standardized unit that can provide heating, cooling, and ventilation for a complete building or a zone within a building. Unitary HVAC system components are matched and assembled to achieve specific performance objectives by the manufacturer. These systems are typically factory assembled into an integrated package that includes fans, filters, heating coil, cooling coil, refrigeration compressors, controls, and other components as required. As a result, unitary HVAC systems are only available in pre-established increments of capacity with set performance parameters unless they are custom ordered and built.

4.3 UNITARY HVAC SYSTEM OPERATION

4.3.1 Unitary HVAC System Operation

Each unitary HVAC system includes its own self-contained mechanical refrigeration cycle as illustrated in Figure 4-1. From Figure 4-1 it can be seen that mechanical refrigeration is achieved by continuously circulating a fixed amount of refrigerant in a closed loop where it is systematically evaporated, compressed, condensed, and finally expanded to transfer heat from one place to another. For conventional unitary HVAC systems, heat is removed from the zone being cooled and rejected to the outside environment resulting in air conditioning. This is the same process used in mechanical refrigeration where heat is removed from the inside of a refrigerator or freezer and rejected to the atmosphere outside the refrigerator or freezer enclosure. As will be discussed later in this chapter, unitary heat pumps are also capable of reversing this process and absorbing heat from the outside environment and delivering it to the zone being heated.

Figure 4-1 Refrigeration Cycle



4.3.2 Mechanical Refrigeration Cycle

The mechanical refrigeration cycle starts with the evaporator as shown in Figure 4-1. Evaporation or the change of state from liquid to gas by the refrigerant occurs at low temperature and low pressure by absorbing heat. Heat is absorbed by the refrigerant passing through the evaporator and changes its phase from a low temperature and low-pressure liquid to a low temperature and low-pressure gas. The evaporator in a unitary HVAC system is typically an air-to-refrigerant heat exchanger that transfers heat from the air to the refrigerant by passing air through a coil using a motor-driven fan. The cooled air exits the unitary HVAC system and cools the zone that it serves. The warm liquid refrigerant exits the evaporator through refrigerant piping and enters the next stage of the mechanical refrigeration cycle which is the compressor.

After leaving the evaporator, the refrigerant travels through the connecting refrigeration piping and enters the compressor as a low-pressure, low-temperature gas. The compressor on a unitary HVAC system is typically a hermetically sealed motor-compressor unit where the motor operates in the same enclosure as the compressor surrounded by refrigerant. The compressor unit compresses the incoming low pressure and low temperature refrigerant gas and turns it into a high pressure and high temperature gas at its output.

From the compressor outlet, the high pressure and high temperature refrigerant gas travels through the refrigerant piping to the condenser. Like the evaporator, the condenser is typically a refrigerant-to-air heat exchanger in unitary HVAC equipment. The high temperature refrigerant transfers heat to the lower temperature air by passing air through the condenser coil and exits the condenser as a high-pressure and low temperature liquid. The phase change from gas to liquid by the refrigerant occurs because the refrigerant is cooled as it passes through the condenser and condenses from a gaseous vapor to liquid.

The final stop for the refrigerant in the mechanical refrigeration cycle is the expansion valve which allows the high pressure and low temperature liquid refrigerant to expand resulting in a low pressure and low temperature liquid refrigerant output. The result of this pressure drop at the output of the expansion valve is a low pressure and low temperature liquid input to the evaporator. This is where the discussion of the mechanical refrigeration cycle started. The low pressure and low temperature liquid refrigerant enters the evaporator to absorb heat from the cooling zone and the cycle begins again.

4.3.3 Direct Expansion Unitary HVAC Systems

Unitary HVAC systems are sometimes referred to as direct-expansion (DX) units. Most unitary HVAC systems are DX units. In a DX unitary HVAC system, the evaporator is in direct contact with the air stream being supplied to the zone. As a result, the evaporator serves as both the evaporator in the mechanical refrigeration cycle and as the cooling coil.

4.4 UNITARY HVAC SYSTEM COMPONENTS

4.4.1 Eight Unitary HVAC System Functional Components

As noted above, each unitary system has its own integral refrigeration cycle and is comprised of the following eight functional components:

- Compressor
- Condenser Or Condensing Coil
- Expansion Valve Or Regulator Valve
- Evaporator Or Cooling Coil
- Fan
- Refrigerant
- Refrigerant Piping
- Controls

4.4.2 Compressor

The compressor is an electromechanical device that compresses the refrigerant as it leaves the evaporator as a gas. The compressor in unitary HVAC systems is typically a hermetically sealed motor-compressor unit where the motor operates with the compressor inside a sealed case in the refrigerant. The compressor increases both the temperature and pressure of the refrigerant.

4.4.3 Condenser Or Condensing Coil

The condenser transfers heat from the hot refrigerant to the outside air through convection. The condenser is typically a refrigerant-to-air heat exchanger referred to as the condensing coil. A mechanical fan is normally used by unitary HVAC systems to force air through the condensing coil to affect the heat transfer from the refrigerant to the environment using forced convection.

4.4.4 Expansion Valve Or Regulator Valve

The cooled refrigerant that is in gas or liquid state after passing through the condenser flows through the expansion valve. The expansion valve allows the refrigerant to quickly expand in the evaporator coil. This rapid expansion of the refrigerant makes it very cold and possibly below freezing. The refrigerant's low temperature gives it the ability to absorb heat from the air in the zone that it serves.

4.4.5 Evaporator Or Cooling Coil

The evaporator also serves as the cooling coil in DX units as discussed above. A mechanical fan is usually used in unitary HVAC systems to force air from the zone being conditioned through the evaporator that transfers heat from the warmer air to the cooler refrigerant by forced convection and transfers it to the refrigerant. This process both lowers the temperature of the air passing through it and causes the moisture in the air to condense. Reducing the air temperature removes sensible heat and removing moisture from the air removes latent heat. The transfer of heat energy between the refrigerant in the evaporator coil and the supply air increases the temperature of the refrigerant and gasifies it which is the state that the refrigerant enters the compressor and begins the cycle again.

4.4.6 Fan

One or more fans are incorporated into unitary HVAC systems to force air through air-to-refrigerant and refrigerant-to-air heat exchangers that are typically referred to as cooling and condensing coils, respectively. In addition to forced convection, these fans are also used to provide necessary ventilation to the building or zone served as well as free cooling when outside air conditions are right.

4.4.7 Refrigerant

The refrigerant is the primary heat transfer medium used in a unitary HVAC system.

4.4.8 Refrigerant Piping

Refrigerant piping that connects the compressor, condenser, expansion valve, and evaporator and provides a closed loop for the refrigerant.

4.4.9 Controls

Controls for unitary HVAC systems control system operation and typically consist of a single thermostatic control located in the building or zone served by the unitary HVAC system.

4.4.10 Other Components

In addition, other components may also typically be added to the eight primary components such as heating coils and humidifiers to provide a unitary HVAC system tailored to the occupancy's particular HVAC needs.

4.5 UNITARY HVAC SYSTEM CATEGORIES

Unitary HVAC systems can be categorized based on their ability to heat as well as cool the building or zone within the building that they serve. Based on this criterion, unitary HVAC systems can be categorized as follows:

- Conventional Unitary HVAC Systems
- Unitary Heat Pump Systems

Conventional unitary HVAC systems operate using the mechanical refrigeration cycle to cool a building or zone. If a conventional unitary HVAC system is also required to heat the building or zone then a separate means of heating the supply air must be incorporated into the system. Heating using conventional unitary HVAC systems is usually accomplished by adding separate hot water, steam, or electric heating coils in the unit. The fan pushes a mixture of return and outside air through the heating coil and the supply air is heated by convection. When the unit is in the heating mode, the refrigeration cycle is shut down.

In contrast to conventional unitary HVAC systems, unitary heat pump systems provide the required heating function by reversing the mechanical refrigeration cycle and absorbing heat from the outside environment and delivering it to the building or zone served. A unitary heat pump system eliminates the need for a separate heat source in the form of hot water, steam, or electricity. As a result, unitary heat pump systems are usually more efficient than conventional unitary HVAC systems when heating is required.

4.6 CONVENTIONAL UNITARY HVAC SYSTEMS

4.6.1 Conventional Unitary HVAC Systems

Conventional unitary HVAC systems can be categorized as follows based on the way that they are physically installed:

- Single-Packaged Units
- Split-Systems
- Packaged Terminal Air Conditioners

Each of these categories of conventional unitary HVAC systems will be discussed in the sections that follow.

4.6.2 Single-Packaged Units

A single-packaged unit is an outdoor unitary HVAC system that is usually installed to cool, heating, and ventilate an entire building or a zone within it. The complete system consists of the packaged HVAC unit itself along with a ducted air distribution system and a temperature control system. The packaged HVAC unit is usually installed on a building roof where it is referred to as a rooftop unit (RTU) but the unit can also be installed on grade outside the building.

When a single unit is used to condition the entire building, the unitary HVAC system and associated ductwork constitute a central station all-air system. Larger buildings often require multiple rooftop units that can either be controlled to operate as a single unit or, more commonly, operate independently allowing the building to be zoned for each unit. Where a building uses single-packaged units and needs to be zoned to address varying HVAC requirements, the zoning can be accomplished by using multiple smaller single packaged units or a single larger that is designed for multizone use. Using smaller single-packaged units provides redundancy and protection against loss of HVAC in the entire building if a single unit fails but a larger single unit will usually provide more efficient operation.

In addition to providing cooling and heating for entire buildings, single-packaged units can be used in conjunction with other types of unitary HVAC systems to meet the needs of a building. For example, single-packaged units could be used to serve the core zones of a building while perimeter zones are served by packaged terminal air conditioners discussed in Section 4.7.4. Single-packaged units are usually used in low-rise buildings consisting of one or two stories.

4.6.3 Split Systems

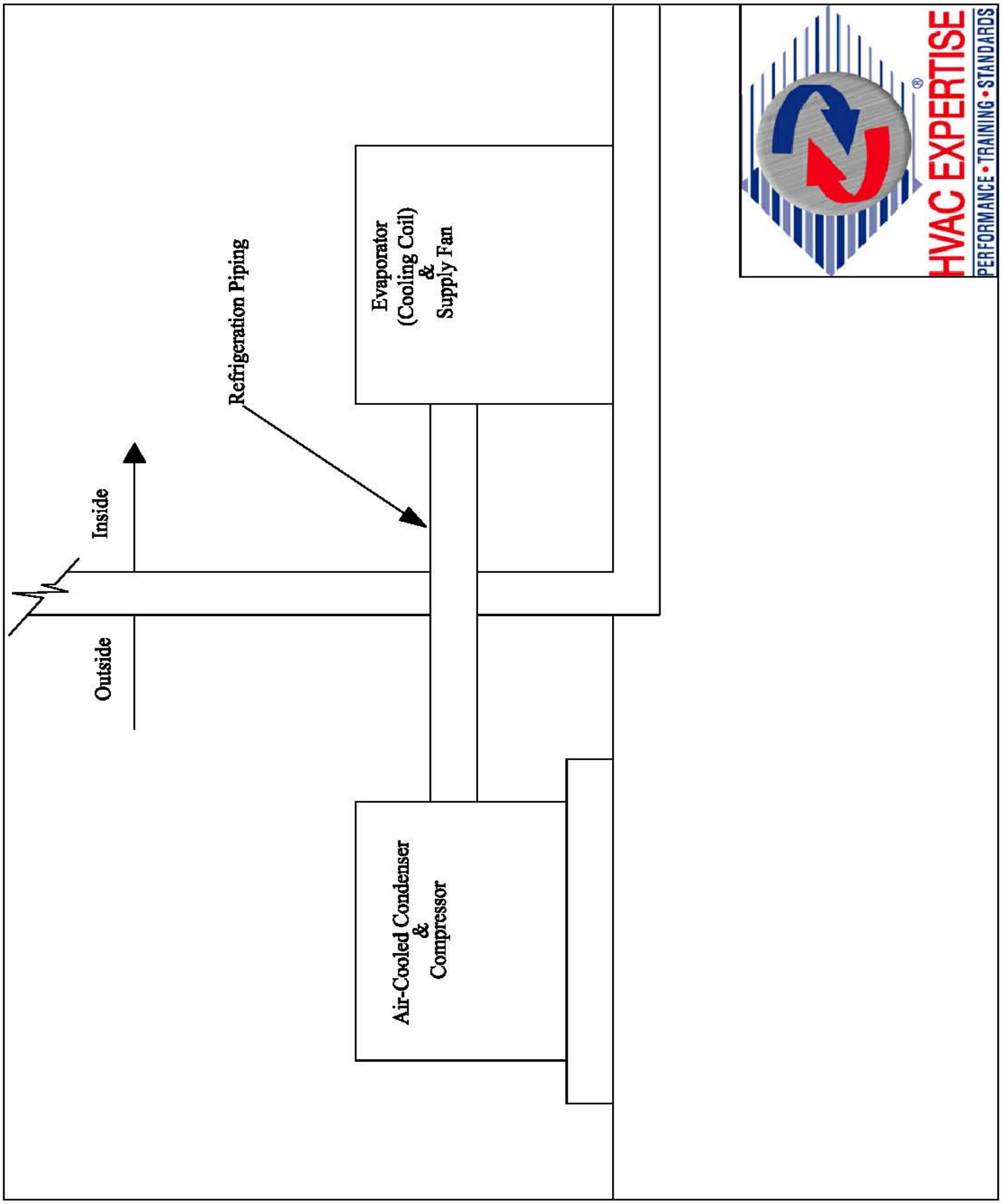
Split unitary HVAC systems can be used to cool and heat an entire building or a zone within the building. A split unitary HVAC system consists of an indoor unit, a remote outdoor air-cooled condensing unit, a refrigerant piping system that connects the two units, a duct system for distributing air throughout the building, and a temperature control system. Split unitary HVAC systems are typically DX systems where the outdoor unit usually consists of an air-cooled condenser and compressor and the indoor unit consisting of the evaporator and regulator valve. The two subsystems are linked by refrigeration piping which limits the distance between them. Figure 4-2 illustrates a split DX system that is commonly used in small commercial buildings and residential applications. Multiple unit systems can be used for small office buildings, standalone retail stores, strip malls, apartment buildings, and similar occupancies where loads vary between occupancies and individual control is desired.

4.6.4 Packaged Terminal Air Conditioners

A packaged terminal air conditioner (PTAC) is a single-zone, constant-volume unitary HVAC system. A PTAC unit is usually a fully self-contained unit that has all the needed system components including controls contained within its enclosure. A simple residential window air conditioning unit is a PTAC unit. However, in most commercial applications PTAC units are permanently installed directly in the wall. For energy conservation purposes, PTAC units can be controlled by occupants during regular building operating times and centrally operated during unoccupied times.

PTAC units are typically installed in the perimeter wall of the building to allow the air-cooled condenser to reject heat directly to the outdoors and to provide direct access to outside air for the space served. PTACs are often used in hotels, dormitories, nursing homes, and apartments where individual rooms each constitute a zone and can be individually controlled for the occupant’s comfort.

Figure 4-2 Split-System Unitary HVAC System



4.7 UNITARY HEAT PUMPS

4.7.1 Unitary Heat Pump Types

As noted previously, unitary heat pumps differ from conventional unitary HVAC systems in that their mechanical refrigeration cycle can be reversed. Reversal of the mechanical refrigeration cycle allows heat to be absorbed by the refrigerant from the outside environment and transferred to the building or zone served by the unit. As a result, unitary heat pumps do not need a separate heating coil and associated source of heat energy such as hot water, steam, or electric resistance to heat the supply air to a building or zone.

Like other unitary HVAC equipment, unitary heat pumps are produced and delivered by the manufacturer as a complete unit. The following two types of unitary heat pump systems are commonly found in small commercial and residential buildings:

- Air-To-Air Unitary Heat Pumps
- Water-To-Air Unitary Heat Pumps

The following sections will discuss these two types of unitary heat pumps.

4.7.2 Air-To-Air Unitary Heat Pumps

An air-to-air unitary heat pump uses an air-to-refrigerant heat exchanger to reject heat to the outdoor air when cooling indoor air and extracts heat from outdoor air when heating indoor air. Like other unitary HVAC systems, air-to-air unitary heat pumps usually consist of factory-matched refrigerant cycle components that are designed and manufactured for use as a unit whether they are contained in one enclosure or multiple enclosures. Air-to-air unitary heat pumps can either be supplied as a single-packaged unit or a split system and closely resemble conventional unitary HVAC systems of equal cooling capacity.

Air-to-air unitary heat pumps are more common than water-to-air unitary heat pumps because air is a universally available heat source. Air-to-air unitary heat pumps can be installed as a multiunit installation that includes a number of individual units that permits zoning and provides the opportunity for heating or cooling in each zone on demand.

Many of the air-to-air unitary heat pump designs and installations are very similar to conventional unitary HVAC systems described earlier in this chapter. Most residential applications are split systems consisting of an indoor fan and coil unit and an outdoor fan-coil unit. The compressor is usually located in the outdoor unit.

4.7.3 Water-To-Air Unitary Heat Pumps

Water-to-air heat pumps use water as the heat source when in the heating mode and as the heat sink when in the cooling mode. A refrigerant-to-water heat exchanger is used as a refrigerant heat sink when cooling indoor air and as a refrigerant heat source when heating indoor air. The water supply may be closed water loop system where water is circulated through a closed loop water-to-earth heat exchanger or open loop where the water is extracted from a lake, stream, or ground well, circulated through the heat exchanger, and then either stored for other uses or returned to its source. An open loop system is also referred to as a one-pass system and is not as common as closed loop water-to-earth heat exchangers because an open loop system needs to be located near either a manmade or natural water supply and there may be environmental and water-use concerns about an open-loop system.

Water-to-air heat pumps that used closed-loop water-to-earth heat exchangers take advantage of the fact that the earth's temperature is relatively constant just a few feet below its surface no matter what the climactic conditions are at the surface. As a result, circulating water is heated when the heat pump is operating in the cooling mode during the summer months and the water's excess heat is transferred to the cooler earth that serves as a heat sink. Similarly, when the heat pump is operating in the heating mode during the winter months the earth serves as a heat source heating the circulating water. Heat pumps that used closed-loop water-to-earth heat exchangers are often referred to as ground-source, earth-coupled, or geothermal heat pumps.

Even though air-to-air unitary heat pumps are more common, water-to-air unitary heat pumps have the following advantages:

- A water-to-air unitary heat pump maintains a fairly constant capacity since the heat source is only available over a limited temperature range.
- A water-to-air unitary heat pump can operate at a higher efficiency if its source water has a constant temperature that is relatively high compared to the outside air.
- A water-to-air unitary heat pump is able to operate without the need for defrosting.

Storage tanks with solar assisted heating can be also incorporated into either a closed or open water-to-air heat pump system. Additionally, the heated water can also be passed through a water-to-water heat exchanger to heat domestic hot water before being circulated back into the earth or returned to the outside environment.

4.7.4 Multiple Split-System Heat Pumps

Instead of installing a conventional single split-system heat pump that conditions the air and then delivers it throughout the building via air ducts, multiple split-system heat pumps can be installed throughout a building. A multiple split-system heat pump is sometimes referred to as a mini-split system. These systems use a single outside condenser-compressor unit and a refrigerant piping system to circulate refrigerant to indoor air-handling units that include a refrigerant-to-air heat exchanger and fan spread throughout the building. These systems are also referred to as ductless systems because no ductwork is required to condition the zones served. These systems are typically only used for cooling but could also be used for heating.

4.8 COMBINATION UNITARY & CENTRAL HVAC SYSTEMS

Unitary HVAC systems that heat and cool perimeter spaces are often used as part of a combination system that also include a central HVAC system. Combination systems can provide better humidity control, air quality, and ventilation than can be obtained with unitary systems alone. The central HVAC system is often able to serve interior building spaces that cannot be conditioned using PTAC units.

CHAPTER V
CENTRAL HEATING EQUIPMENT

5.1 INTRODUCTION

This chapter covers central heating equipment including furnaces and boilers. Furnaces are first discussed followed by a discussion of boilers and associated equipment including boiler feedwater pumps and deaerators. Other central heating systems including solar and combined heat and power (CHP) are also discussed.

5.2 FURNACES

Furnaces are used in residential and small commercial buildings for heating. A furnace is essentially an all-air heating system that uses air as its primary heat transport medium. A furnace is typically the central heating system and supply air is heated in the furnace and then delivered to spaces via ducts throughout the building. Central heating systems using a furnace for heat typically include a fan to pull return air from the space and push air through the furnace for conditioning and then through the air distribution system for delivery to the space.

The most common fuel source for furnaces is natural gas although other common fuel sources include liquefied petroleum (LP) gas, fuel oil, and wood. Electric furnaces use electric elements to heat the air passing through them. These electric element used is typically a simple electric resistance heating coils. Furnaces using combustion as their heat source always require venting to exhaust combustion gases and avoid the buildup of gases such as carbon monoxide in the building. Electric furnaces on the other hand do not require venting because there is no combustion that result in gases that must be exhausted.

Electric furnaces are also available and are used either where electricity is less expensive than available combustion fuels, combustion fuels are not available, there is concern that the byproducts of combustion could enter the air stream and contaminate zone served, or it is not possible or practical to vent combustion gases. Electric furnaces heat the air passing through them using electric elements. These electric elements are usually just simple electric resistance heating coils but could be other materials that heat up when electric current passes through them. As a result, electric furnaces do not rely on combustion to heat the air and do not produce gases that require venting. This feature makes electric furnaces a good choice where additional heat is needed for an interior building zone or space and the routing of gas piping through the building to a conventional natural gas furnace along with the need to exhaust combustion gases is not practical.

Furnaces, like boilers, can be classified as either condensing or non-condensing. Condensing furnaces are much more efficient than non-condensing or traditional furnaces. A condensing furnace extracts heat from flue gases before they are exhausted and uses this heat to improve the efficiency of the combustion process. What is waste heat in a conventional furnace is used in a condensing furnace to improve its efficiency. However, condensing furnaces must be designed to withstand the highly corrosive condensate that results from the cooling of exhaust combustion gases. Therefore, the first cost of a condensing furnace is higher and the decision to use a condensing furnace over a traditional or non-condensing furnace should be based on a life-cycle cost analysis.

5.3 BOILERS

Where furnaces use air as their primary heat transfer medium, central heating plants with boilers use water as their primary heat transfer medium. Boiler-based central heating plants are used almost exclusively in larger commercial and institutional buildings over furnaces because hot water or steam is easier and more economical to distribute than air. Hydronic piping takes up less room in a building than ductwork, has much less heat loss than ductwork making it more efficient, and can be routed through the building much easier. As a result, central heating plants use boilers and hydronic distribution systems in all but the smallest of buildings or where the function of larger commercial buildings requires them to be broken up into small independently heated zones as in the case of a high-rise condominium or apartment building.

The purpose of a boiler is to transfer heat from a heat source to water by conduction which can then be circulated through a building to provide heat. This is a hydronic heating system because water is the primary heat transport medium. The boiler raises the temperature of the water and the water is distributed throughout the building as either hot water or steam via the piping system. When the boiler produces steam, it is referred to as a steam boiler. Hot water boilers are typical in most commercial and institutional HVAC systems today and the boilers used in these systems are referred to as hot water boilers. Steam boilers and distribution systems can still be found in older buildings but steam is not commonly used in commercial or institutional buildings today.

Hot water systems are normally more efficient than steam systems in commercial and institutional buildings which is why hot water boilers are more common than steam boilers today. However, steam does have advantages in some applications. In most cases, steam is selected over hot water when there is a need for large amounts of heat to be delivered quickly as in the case of a building that requires 100 percent outside air. Similarly, steam is also the better choice for multi-building complexes that have a heating plant that serves the entire complex from a central location such as multi-building commercial developments, schools, and health-care facilities. It is easier to distribute steam over large areas to multiple buildings as well as handle fluctuating building loads than it would be with hot water. However, steam generation and distribution systems require more maintenance and are generally more costly than hot water systems both on a first cost and ongoing basis and should be avoided for commercial and institutional buildings unless there are other overriding reasons to select a steam system.

The hot water or steam warms the space by transferring its heat to the surrounding air through water-to-air or steam-to-air heat exchangers. In an air-hydronic HVAC system, the heat exchanger would be located in the air stream like a heating coil installed in an air handling unit where the air passing through it is heated before it is delivered to the space. The heat exchanger could also be located in the space and heat could be transferred directly to the space as in the case of a common radiator. As the hot water or steam circulates through the building providing heat, it gives up energy and cools. The water or steam is then retuned to the boiler for reheating and the cycle starts again.

5.4 BOILER SIZING

Boilers are sized based on their heat capacity. Smaller boilers are usually rated in British thermal units (Btu) per hour and larger boilers are typically rated in boiler horsepower. Since Btu is a unit of energy as discussed in Chapter II, the rate of energy usage in Btu per hour is power and can be related to horsepower. One boiler horsepower is equivalent to 33,475 Btu per hour. Typical boiler size ranges for various types of facilities are provided in the following table:

FACILITY	BOILER SIZE	
	HEAT RATE (Btu/hr)	HORSEPOWER (bhp)
Small Commercial Or Residential	67,000 – 3,400,000	2 – 100
Medium Commercial & Small Industrial	2,500,000 – 10,000,000	100 – 300
Large Commercial & Large Industrial	10,000,000 – 33,500,000	300 - 1000

5.5 BOILER CONSTRUCTION

5.5.1 Boiler Construction

Boilers are often classified according to their construction. Boilers can be either of the following:

- Fire Tube
- Water Tube

5.5.2 Fire-Tube Boilers

Fire-tube boilers are typically constructed with a cylindrical outer shell and a number of tubes passing through the outer shell. With a fire-tube boiler, hot gases from the combustion of fuel are passed through the tubes that are surrounded by water in the outer shell. Heat is transferred from the tubes to the water which is then circulated through the building as either hot water or steam. Fire-tube boilers are also often classified as to the number of times the combustion gasses pass through the boiler heating the water before being exhausted referred to as the number of passes through the boiler. At the end of their run through the boiler, the tubes make a 180-degree turn and pass back through the boiler releasing additional energy and making the boiler more efficient. The turnaround can either be dry-back where the 180-degree turn is made outside the boiler shell or water-back where the 180-degree turn is made within the boiler shell. As steam generators, fire-tube boilers are limited to the amount of pressure that they can produce because the water is located in the cylindrical shell which has a large surface area.

Scotch marine boilers are the most common fire-tube boiler because of their low initial cost and high efficiency and durability. Scotch marine boilers typically contain a large volume of water that allows them to respond to load changes in the building.

5.5.3 Water-Tube Boilers

Water-tube boilers operate just the opposite of fire-tube boilers. With water-tube boilers, the water passes through the boiler tubes and the hot combustion gases pass over the boiler tubes in the outer shell of the boiler. With their smaller surface area, the water tubes can be built to withstand higher pressures that the shell in a fire-tube boiler so water-tube boilers are typically used where high steam pressures are required. Water-tube boilers are typically used in manufacturing and process industrial applications where high-pressure steam is required such as in electric power generation. Water-tube boilers are typically not used in commercial or institutional HVAC systems.

5.6 ELECTRIC BOILERS

Electric boilers like electric furnaces use electric heating elements either to produce hot water or steam depending on the type of boiler needed. Electric boilers do not need to be vented since they do not produce any combustion gases that need to be exhausted such as carbon monoxide. Electric boilers may be the right choice where hot water or steam is required in an existing facility but there is no way to vent the combustion gases or in locations where electric rates are low. Also, electric boilers may be used in conjunction with boilers using natural gas and other fuels where the cost of off-peak electricity or an interruptible electric rate makes the electric boiler the more economical source of hot water or steam at night or other off-peak times.

5.7 CONDENSING BOILERS

Conventional boilers have an efficiency of better than 80 percent whereas energy-efficient condensing boilers have a rated efficiency above 90 percent. Condensing boilers are more efficient because they absorb more heat from the combustion gases using very high efficiency heat exchangers. However, extracting this much heat from the combustion exhaust stream results in the water contained in the exhaust combustion gases to condense which is very corrosive.

Conventional boilers are constructed using materials that cannot withstand the corrosive affects of the condensing flue or stack gases as discussed in the previous section. Any hydrocarbon fuel that is burned in the boiler including natural gas produces water vapor during the combustion process. The difference between a conventional boiler and a high-efficiency condensing boiler is the ability of the condensing boiler to withstand the corrosive affects of the flue gas condensate through their design and the materials used to construct them.

Like condensing furnaces, condensing boilers have a higher first cost because they need to be able to withstand the corrosive flue gas condensate in order to achieve the higher efficiencies that they are noted for. As a result, the increased energy savings that result from its higher efficiency over its useful life must offset the increased first cost of a condensing boiler over a conventional boiler. A life cycle cost analysis should be performed when considering a condensing boiler.

5.8 BOILER AUXILIARY EQUIPMENT

5.8.1 Boiler Circulating Pumps

Circulating pumps in hot water systems circulate the hot water throughout the building by way of the hydronic piping system and return it to the boiler for reheating. Typically, the hydroni8c piping system will be designed and installed with a primary and secondary loop which requires a circulating water pump for both loops. The primary loop pump circulates through the boiler continuously while the secondary loop pump circulates the hot water throughout the building for heating. Circulating pumps should use energy efficient motors and variable frequency drives (VFDs) where appropriate. Circulating pumps with VFDs can increase system efficiency in the same way that VFDs increase the efficiency of fans and air distribution systems.

5.8.2 Deaerators

A deaerator is a device that removes corrosive gasses from boiler feedwater to make it noncorrosive. Oxygen, carbon dioxide, and other dissolved gases can be very corrosive and need to be eliminated from boiler feedwater to prevent damage to the boiler. Oxygen is the most corrosive gas and it can be introduced into the boiler feedwater through the addition of makeup water or leakage in the return hydronic system. Dissolved gases along with suspended solids should be removed from boiler feedwater to avoid corrosion in the boiler. Deaeration can be accomplished by either mechanical or chemical means. Dissolved gases including oxygen can be removed chemically by water treatment but are most often removed using a mechanical deaerator.

5.9 BOILER CONTROLS

5.9.1 Boiler Control Methods

Boiler operation is controlled in the following ways:

- Burner Control
- Supply Water Temperature Control
- Combination Burner & Supply Temperature Control

Hot water boilers typically utilize burner control based on the temperature of the incoming water. The control is set to maintain a 140^{o} –180^{o} F water temperature at the boilers output. Steam boilers are typically controlled based on a pressure setpoint that is typically 5 – 10 pounds per square inch (psi).

5.9.2 Boiler Burner Control

Boiler burner control is designed to control the rate of fuel input in response to some control signal representing load change. The objective of boiler burner control is to have the average boiler output equal heating load within some acceptable control tolerance. Boiler burner controls also include safety controls that act to shut off fuel flow when unsafe conditions develop. Boiler operation can be controlled in the following three ways:

- On-Off Control
- Low-High-Low Control
- Modulating Control

On-Off Control. On-off control is basically a binary control where the boiler cycles on and off depending on the building load being served by the boiler. This is the least expensive first cost control system but is also the least efficient control system over the life of the installation. On-off control is the least efficient because of the losses associated with each cycle. Also, oversized boilers will result in frequent cycling further reducing efficiency.

Low-High-Low Control. Low-high-low control is more efficient and effective than just a simple on-off control by cycling between a high and low burner setting to maintain the hot water temperature and meet the building's changing heating load.

Modulating Control. Modulating control is the most efficient boiler control method of the three and best at meeting the building's changing heating load. With modulating control, the burner is adjusted or modulated on a continuous basis to meet the building's heating load. At low fire conditions the flow of combustion gases through the boiler is less and more of the heat from these combustion gases can be captured and used.

CHAPTER VI
CENTRAL COOLING EQUIPMENT

6.1 INTRODUCTION

Central cooling equipment is covered in this chapter which includes chillers and cooling towers. This chapter starts with a description of a central cooling plant followed by a detailed discussion of chiller operation including the chiller refrigeration cycle, chiller components, types of chillers commonly used to supply chilled water in commercial and institutional buildings. Cooling towers operation, types and construction are then discussed. This chapter finishes with a discussion of evaporative cooling systems.

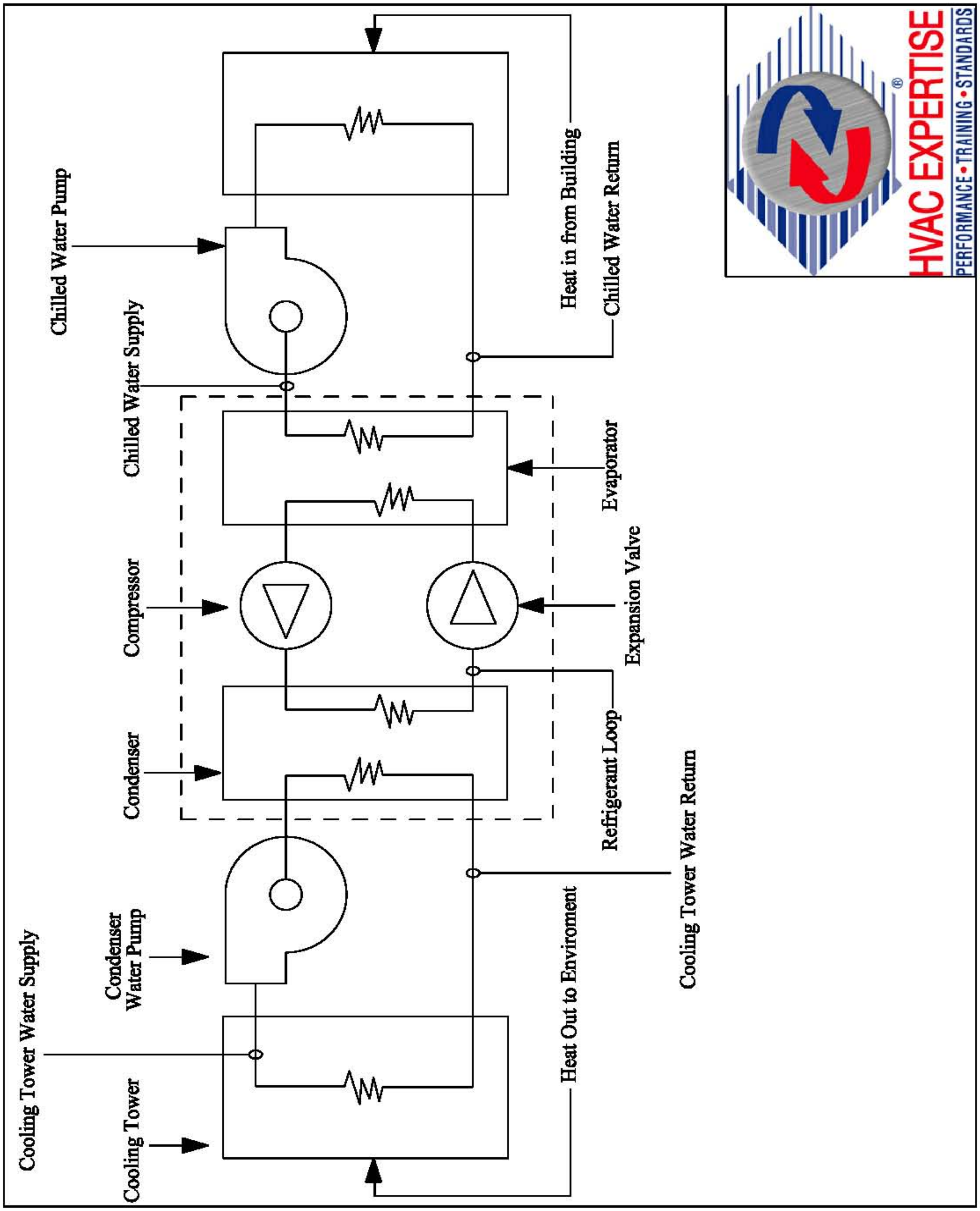
6.2 CENTRAL COOLING PLANT OPERATION & COMPONENTS

A schematic diagram of a central cooling plant showing the major components and how they are related is shown in Figure 6-1. This central cooling plant uses a water-cooled chiller and a cooling tower to extract heat from the interior of the building. As will be discussed in this chapter, the central cooling plant could have also used an air-cooled chiller in which case the condenser water loop circulating through the cooling tower and the cooling tower would not be needed. Instead the heat from the building would be rejected to the outside environment from the condenser using a refrigerant-to-air heat exchanger.

The central cooling plant in Figure 6-1circulates chilled water throughout the building using a hydronic distribution system as discussed in Chapter VII. The system is designed so that the chilled water is supplied at 44°F at the output of the chiller, absorbs heat as the chilled water passes through air-to-water heat exchangers such as air handling unit cooling coils throughout the building, and then returns to the chiller at 54°F. The chiller extracts the heat from the returning chilled water and starts the cycle again by supplying 44°F chilled water to the hydronic distribution system.

The heat removed from the returning chilled water is absorbed by refrigerant circulating in the chiller and transferred to the cooling tower water loop using the vapor-compression refrigeration cycle as discussed in this chapter. The cooling tower is supplied with 95°F condenser water and by evaporation reduces the temperature of the condenser water to 85°F and then recycles it back to the condenser to start the cycle again.

Figure 6-1 Central Cooling Plant Schematic Diagram



6.3 CHILLER PURPOSE

Chillers are the key element in a central cooling plant. Chillers are machines that extract heat from the facility by cooling the water that is circulated around the facility to absorb the heat. The water circulated around the facility is typically referred to as “chilled water” and because it is the heat transfer medium for the building’s cooling system it is also often referred as the “secondary fluid” with the chiller refrigerant being the “primary fluid” in the heat transfer process. Both sensible and latent heat are transferred to the chilled water when it is pumped through cooling coils within air handling units (AHUs), fan coils, or any component of the air-conditioning system that acts as an air-liquid heat exchanger whose purpose is to remove the heat energy from the air passing through it. The affect of this air-to-water heat transfer is to condition the air delivered to a zone by cooling and dehumidifying it. Chiller size is typically expressed in tons of cooling capacity and chillers manufactured for commercial HVAC applications range in size from about 15 to more than 1500 tons.

6.4 REFRIGERATION CYCLE

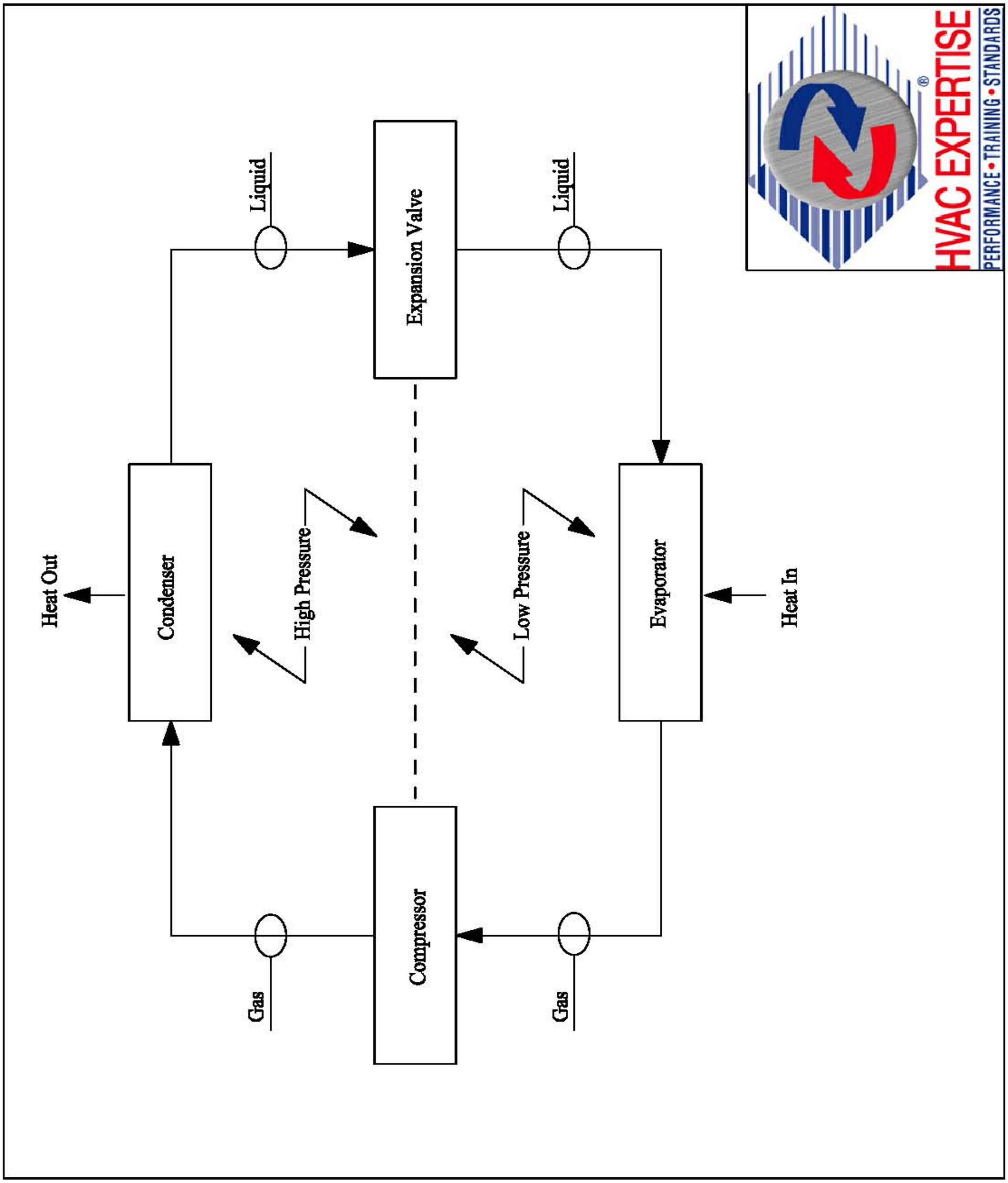
6.4.1 Chiller Refrigeration Cycle

Chillers are essentially refrigeration systems that extract heat from the circulating chilled water using a refrigeration cycle. Chillers use a vapor-compression refrigeration cycle which is also known as a reverse Rankine refrigeration cycle to cool the circulating chilled water in a building. This refrigeration cycle is similar to the refrigeration cycle used in unitary HVAC systems that was described in Chapter IV. The main difference between the chiller refrigeration cycle and the unitary HVAC system is that chillers chill water that is used to cool the supply air to a building zone using a water-to-air heat exchanger and unitary HVAC systems chill the air supplied to the zone directly using a refrigerant-to-air heat exchanger.

Figure 6-2 provides a schematic diagram of the vapor-compression refrigeration cycle for a chiller that contains the same four components as the unitary air-conditioning system refrigeration cycle shown in Figure 4-1. Each of these components provides the same function as it does in a unitary air-conditioning system. The refrigeration cycle extracts heat from the building using a refrigerant circulating in a closed loop. The heat absorbed by the refrigerant is then rejected to the outside atmosphere using either a water-to-air or refrigerant-to-air heat exchanger. The four mechanical components that comprise a chiller and allow it to chill water through the vapor-compression refrigeration cycle are as follows:

- Compressor
- Condenser
- Expansion Valve
- Evaporator

Figure 6-2 Vapor-Compression Refrigeration Cycle



The purpose and function of each of these four components are discussed in the paragraphs that follow. Each of these four components operates exactly the same as it does in a unitary air-conditioning system. However, because of the size and complexity of chillers and central cooling plants and the need to provide an efficient system that economically meets the unique air-conditioning needs of the facility it serves, there a number of alternative chiller configurations.

6.4.2 Compressor

Compressor Function And Types. The function of a compressor in the vapor-compression refrigeration cycle is to compress the refrigerant from a low-pressure vapor to a high-pressure vapor. There are two major categories of vapor-compression refrigeration cycle water chillers used to produce chilled water for air conditioning in commercial buildings today. These two chiller categories are based on the type of compressor used in the refrigeration cycle and are as follows:

- Mechanical Chillers
- Absorption Chillers

Mechanical Chillers. As the name implies, mechanical chillers employ a mechanical compressor to compress the refrigerant. The mechanical compressor that is used to compress the refrigerant is usually a centrifugal, reciprocating, scroll, or rotary screw compressor. These mechanical compressors are driven by a variety of prime movers that include electric motors, steam turbines, diesel engines, and others. However, the most common means of driving a chiller compressor in a commercial building air-conditioning application is a three-phase electric induction motor although large chillers sometimes use synchronous motors.

Each of these types of mechanical compressors has unique operating characteristics that make it the preferred choice for a particular chiller size or chiller application. In fact, a mechanical chiller is often classified and referred to by the type of compressor that it employs. For example, a mechanical chiller employing a centrifugal compressor will often be referred to generically as a centrifugal chiller. Each of these compressor types will be discussed in more detail in this chapter. However, when selecting a chiller for a particular application, manufacturers should be consulted because compressor technologies, ratings, and efficiencies are constantly improving and a compressor type that may have not been suitable for an application in the past may be the preferred alternative today.

Absorption Chillers. Absorption chillers do not have a mechanical compressor but instead use a thermochemical compressor. Absorption chillers are classified according to the heat source that they use to drive their thermochemical compressor. Absorption chillers are classified by their heat source as either of the following:

- Direct-Fired
- Indirect-Fired

Direct-fired absorption chillers include a burner that burns a fuel to produce the heat needed for the absorption refrigeration cycle. Typical fuels used to provide the necessary heat for the absorption refrigeration cycle include natural gas and No. 2 fuel oil. Indirect-fired absorption chillers use either waste hot water or steam produced by an external boiler, industrial process or other source to drive the absorption refrigeration cycle. Indirect-fired absorption chillers are often used in combiner heat and power (CHP) or cogeneration applications.

A second classification of absorption chillers comes from the number of refrigeration cycles that are incorporated into the chiller. Absorption chillers can be classified as either:

- Single-Effect
- Multiple-Effect

Single-effect absorption chillers incorporate one refrigeration cycle into their operation whereas multiple-effect absorption chillers incorporate two or more refrigeration cycles into their operation. Multiple-effect absorption chillers are more efficient than single-stage absorption chillers but multiple-effect absorption chillers require more thermal energy in the first stage that restricts many applications to a single-effect absorption chiller. Absorption chiller operation will be discussed in more detail later in this chapter.

6.4.3 Condenser

Condenser Function And Types. Following the compressor in the refrigeration cycle is the condenser. The function of the condenser is to reject the heat from the chiller so the condenser is essentially a heat exchanger. Chiller condensers for commercial air conditioning applications remove heat from the refrigerant using either a refrigerant-to-water heat exchanger or a refrigerant-to-air heat exchanger. The type of condenser or heat rejection method is another way that a chiller is classified and referred to. There are two classifications of chillers used in commercial air-conditioning systems based on heat rejection method. These two chiller classifications are as follows:

- Water-Cooled Chillers
- Air-Cooled Chillers

For a water-cooled chiller, heat is normally rejected to the atmosphere via a cooling tower located outside the building. Cooling towers are discussed later in this chapter. For an air-cooled chiller, heat is rejected to the atmosphere by an air-cooled condenser that is located outside the building. In either case, the refrigerant enters the condenser as a vapor and leaves as a liquid.

Water-Cooled Chillers. Water-cooled chillers use water to remove heat from the condenser. In a water-cooled chiller, water is circulated through the condenser and heat from the refrigerant is transferred from the refrigerant to the water by a refrigerant-to-water heat exchanger. Typically, water-cooled chillers capture and reject building heat by transferring it first from the refrigerant to the water and then running the water through an outside cooling tower. The cooling tower then extracts the heat from the water and transfers it to the atmosphere. The cooled water is then returned to the chiller to begin the heat transfer cycle again. Alternatively, other sources of water can be used to cool the refrigerant such as water supplied by the building's water utility, water from a well, water from a nearby pond established for this purpose. Water-cooled chillers are typically 100 tons of cooling capacity or greater and are usually located indoors and their associated cooling towers are located outdoors.

Air-Cooled Chillers. Air-cooled chillers reject the heat extracted from the building directly to the atmosphere using a condenser that is essentially a refrigerant-to-air heat exchanger. Air is drawn across the condenser by fans and heat is transferred to the atmosphere by the refrigerant-to-air heat exchange. Air-cooled chillers are typically less efficient than water-cooled chillers because heat rejection for a water-cooled chiller with a cooling tower takes place at or near the outside air's wet-bulb temperature whereas heat rejection for an air-cooled chiller occurs at the higher dry-bulb temperature.

Air-cooled chillers are manufactured in two basic configurations. In one configuration, the air-cooled chiller is manufactured as a unit with all components in a single enclosure that is either located outside on grade near the building or on the building roof. Integrated air-cooled chillers are typically referred to as packaged units and are the most common configuration. However, the air-cooled chiller could be supplied into two parts like a split unitary air-conditioning unit. With a split air-cooled chiller, the condenser is installed somewhere outside the building like a packaged unit and the other components that comprise the air-cooled chiller are located inside the building. Refrigerant piping connects the inside unit with the outside condenser which usually requires that the two be located close to one another such as having the condenser unit installed on the roof and the remaining equipment installed on the floor directly below.

6.4.4 Expansion Valve

The next mechanical device in the refrigeration cycle is the expansion valve that is also sometimes referred to as the metering device. The purpose of the expansion valve is to control the transfer or meter the high-pressure refrigerant from the condenser into the low-pressure evaporator.

6.4.5 Evaporator

The last major component in the chiller's vapor-compression refrigeration cycle is the evaporator or water cooler. The evaporator is the mechanical component that actually cools or chills the water that is circulated throughout the building to collect heat. Like the condenser, the evaporator is a refrigerant-to-water heat exchanger whose function is to transfer the heat from the circulating water to the refrigerant. The evaporator is typically a shell and tube heat exchanger. The incoming refrigerant is in a liquid-vapor mixture and which allows it to absorb heat from the water by changing state and exiting the evaporator as a vapor.

6.5 REFRIGERANT

The refrigerant is the primary heat transfer medium that is circulated in a closed loop within the chiller. The selection of refrigerant is an important consideration in determining equipment and operating costs. In choosing refrigerant, consider coefficient of performance, operating pressures, flow rate, heat transfer properties, stability, toxicity, and flammability. The thermal stability of the refrigerant and its compatibility with materials in contact with it are also very important considerations. Special attention needs to be given to the selection of elastomers and electrical insulating materials because many common materials are affected by the refrigerants

6.6 MOTOR-COMPRESSOR UNITS

6.6.1 Motor-Compressor Unit Types

Compressors require a prime mover that provides rotating mechanical energy that allows them to do the work of compressing the refrigerant in the vapor-compression refrigeration cycle. As noted above, these prime movers can be any type of energy conversion device that has the power to drive the compressor but are typically electric motors. The physical construction of motor-compressor units used in HVAC equipment impacts the type of prime mover that can be used and chiller operation and maintenance costs. Mechanical chiller motor-compressor units can be constructed in either of the following two ways:

- External Drive Motor-Compressor Units
- Hermetically Sealed Motor-Compressor Units

Both external drive motor-compressor units and hermetically sealed motor compressor units are available. The following paragraphs will discuss each of these options.

6.6.2 External Drive Motor-Compressor Units

An external drive machine uses a compressor that is driven by a prime mover that is external to the compressor and transfers rotating mechanical energy to it through a common external shaft. External drive motor-compressor units are typically used when a prime mover other than an induction motor is used to drive the compressor. External drive motor-compressor units can use a steam or gas turbine, internal combustion engine, synchronous electric motor, induction electric motor, or other prime mover to drive the compressor. The advantage of an external dive motor compressor unit over a hermetically sealed motor-compressor unit is that the prime mover is easily accessible for maintenance, repair, or replacement. The disadvantage is that a drive shaft seal is required in the compressor to contain the refrigerant and oil and from escaping into the atmosphere that requires regular inspection and maintenance.

6.6.3 Hermetically Sealed Motor-Compressor Units

A hermetically sealed motor-compressor unit encloses both the compressor and electric drive motor in the same enclosure with the refrigerant eliminating the need for a drive shaft seal. The electric drive motor operates in the refrigerant atmosphere. As a result, the possibility of refrigerant leakage to the outside atmosphere through the shaft seal is eliminated and the housing reduces motor noise. Since forced refrigerant cooling of the motor is very effective, smaller, less expensive motors can be used with hermetically sealed motor-compressor units. The need for a heavy external base to maintain motor-compressor shaft alignment is also eliminated. As a result, hermetic machines are less expensive than external drive machines build and install, have slightly greater power consumption than a similarly rated external drive machine, and are quieter. However, if the motor should fail the repair costs for a hermetically sealed motor-compressor unit will be higher.

6.7 MECHANICAL COMPRESSOR OPERATION & CHARACTERISTICS

6.7.1 Compressor Types

As discussed in the previous section describing the chiller refrigeration cycle, mechanical chillers employ a variety of mechanical compressors that convert the refrigerant from a low-pressure vapor to a high-pressure vapor. The type of compressor used impacts the mechanical chiller's operating characteristics. Chillers use four common types of mechanical compressors that are as follows:

- Centrifugal
- Reciprocating
- Scroll
- Rotary Screw

The following paragraphs will discuss the operational characteristics of each of these mechanical chiller types.

6.7.2 Centrifugal Compressors & Chillers

Centrifugal compressors raise the pressure of refrigerant by using a rotating impeller to impart velocity to the refrigerant and then convert that velocity to pressure. Chillers using centrifugal compressors are typically large chillers rated above 500 tons of chilling capacity. Centrifugal chiller efficiencies are high at full load but centrifugal chillers do not perform as well at partial load as other chiller types.

Since the centrifugal compressor is not of the constant displacement type, it offers a wide range of capacities continuously modulated over a limited range of pressure ratios. By altering built-in design items including number of stages, compressor speed, impeller diameters, and choice of refrigerant, it can be used in liquid chillers having a wide range of design chilled liquid temperatures and design cooling fluid temperatures. Its ability to continuously vary capacity to match a wide range of load conditions with nearly proportionate changes in power consumption makes it desirable for both close temperature control and energy conservation. Its ability to operate at greatly reduced capacity makes for more on-the-line time with infrequent starting.

Centrifugal packages are currently available from about 80 to 2400 tons at nominal conditions of 44°F leaving chilled water temperature and 95°F leaving condenser water temperature. This upper limit is continually increasing. Field-assembled machines extend to about 10,000 tons. Single-stage, two-stage internally geared machines, and two-stage direct-drive machines are commonly used in packaged units. Electric motor-driven machines constitute the majority of units sold.

Units with hermetically sealed motor-compressor units that are cooled by refrigerant gas or liquid are offered from about 80 to 2000 tons. Open-drive units are not offered by all manufacturers in the same size increments but are generally available from 80 to 10,000 tons. Packaged electric-drive chillers may be of the open- or hermetically sealed motor-compressor type and use three-phase electric motors, with or without speed-increasing gears. Hermetic units use only three-phase induction electric motors.

6.7.3 Reciprocating Compressors & Chillers

Reciprocating compressors are piston-style, positive displacement compressors. Reciprocating compressors are used in chillers because they are typically less expensive than other types of compressors. Chillers with reciprocating compressors are also more economical in smaller sizes than chillers using other types of compressors. With a reciprocating compressor, the chiller's efficiency can be increased at partial load operation by using a variable frequency drive (VFD) or step control. Offsetting their efficiency is the fact that reciprocating compressors have a number of moving parts that can increase their maintenance costs when compared to chillers with other types of compressors.

A distinguishing feature of the reciprocating compressor is its pressure rise versus capacity characteristic. Pressure rise has only a slight influence on the volume flow rate of the compressor and, therefore, a reciprocating liquid chiller retains nearly full cooling capacity even when the actual wet-bulb temperature is above the design wet-bulb temperature. Reciprocating condensers are well suited for air-cooled condenser application and low temperature refrigeration.

Available capacities range from about 2 to 200 tons. Multiple reciprocating compressor units have become popular for two reasons:

- The number of capacity increments is greater resulting in closer liquid temperature control, lower power consumption, less current inrush during starting, and extra standby capacity.
- Multiple refrigerant circuits are employed, resulting in the potential for limited servicing or maintenance of some components while maintaining cooling.

6.7.4 Rotary Screw Compressors & Chillers

Like the reciprocating compressor, a rotary screw or helical rotary compressor is also a positive displacement compressor with nearly constant flow performance. Rotary screw compressors operate by meshing two screw rotors rotating in opposite directions that trap and compress the refrigerant vapor along the rotors to the discharge point. Mid-sized chillers with ratings in the range of 150 to 1,500 tons of chilling capacity often use rotary screw compressors. Rotary screw compressor chillers have fewer moving parts than a comparable reciprocating compressor and typically have lower maintenance costs and a longer useful life. Rotary screw compressors are also efficient at partial load and are capable of adjusting to load swings.

Screw compressor liquid chillers are available as factory-packaged units from about 40 to 850 tons. Both open and hermetically sealed motor-compressor units are manufactured. Additionally, compressor units, comprised of a compressor, hermetic or open motor, oil separator, and oil system, are available from 20 to 2000 tons, for use with remote evaporators and condensers for low, medium, and high evaporating temperature applications. Condensing units, similar to compressor units in range and capacity but with water-cooled condensers, are also built.

6.7.6 Scroll Compressors & Chillers

Scroll compressors are also positive displacement compressors where the refrigerant is compressed when one spiral rotates around a second stationary spiral resulting in high refrigerant pressures at the compressor discharge point. Scroll compressors are usually found in smaller chillers such as rotary heat pumps. Scroll compressors can be up to 10 percent more efficient than a comparably sized reciprocating compressor.

6.8 ABSORPTION CHILLERS

6.8.1 Absorption Chillers In The United States

Absorption chillers are not new. Absorption chillers were first developed, patented, and used in the late 1800’s for cooling. In some parts of the world today, absorption chillers dominate the chiller market because of available energy sources. In the United States, a readily available and reliable electric energy supply and inexpensive electric rates have resulted in limited use of absorption chillers. In the past, absorption chillers have typically been used in commercial building air-conditioning applications under the following conditions:

- Where waste heat energy is available resulting in essentially free chilled water.
- Where utility-supplied electricity is not available but other forms of energy.
- Where other forms of energy such as natural gas, geothermal, or solar are competitive with utility-supplied electric energy.

However, today there is renewed interest in absorption chillers in the United States as the cost of utility supplied electric energy continues to increase at the same time that the availability and reliability of utility-supplied electric energy decreases. Couple this with growing interest in the environment and the drive to sustainable construction and high-performance HVAC systems for commercial buildings and the result is a growing demand for absorption chillers in the United States.

6.8.2 When To Consider An Absorption Chiller

Electric motor driven mechanical chillers are the most common type of chiller used in the United States because of the ready availability of inexpensive electric energy. However, an absorption chiller may be the better choice under certain circumstances. These circumstances include the following:

- There is a source of waste steam or hot water available in the facility that can be used to provide essentially free chilled water.
- There is a source of thermal energy available such as geothermal or solar that can be harnessed and is more economical than utility-supplied electric energy on a life cycle cost basis.
- Electric demand and/or energy charges are high for utility-supplied electric energy.
- Seasonal electricity and natural gas rates that result in higher electric rates and lower natural gas rates during the facility's cooling season.
- Government, utility, or manufacturer financial incentives and rebates that lower the first cost, ongoing operating cost, or both making an absorption chiller more economical than a mechanical chiller on a life cycle cost basis.

Absorption chillers can also be an economical alternative in central plants that have multiple chillers where the advantages of both mechanical chillers and absorption chillers can used to optimize overall central chiller plant's year round operation. For example, absorption chillers could be used during the summer when electricity prices are high and natural gas prices are low and mechanical chillers can be used in the winter when the opposite energy pricing structure is in effect. Also, there may be waste heat available in the winter from boilers that could be used by the absorption chiller to provide any needed chilled water.

6.8.3 Absorption Chiller Operation

As discussed previously, an absorption chiller operates based on a vapor-compression refrigeration cycle just like a mechanical chiller. The difference is in the compressor. Rather than using a mechanical compressor, an absorption chiller uses a thermochemical compressor that requires a refrigerant and an absorbent to operate. For commercial building air-conditioning applications, the refrigerant is usually water which can easily change phase between liquid and vapor. The absorbent is usually either lithium bromide or ammonia and has a high affinity for water meaning that either the refrigerant or absorbent can dissolve easily in the other. This characteristic allows water to boil at a lower temperature and pressure than it normally would at standard temperature and pressure (STP) making it possible to absorb heat from the returning chilled water in the evaporator and then release heat in the condenser.

6.8.4 Direct- Versus Indirect-Fired Absorption Chillers

Direct-fired absorption chillers get the thermal energy they need directly from the combustion of fossil fuels such as natural gas or No. 2 fuel oil. Indirect-fired absorption chillers use waste heat for operation which includes steam and hot water that are byproducts of other processes that effectively provides free energy for chilling water. Indirect-fired absorption chillers are used where heat recovery or cogeneration is possible.

6.8.5 Multiple-Effect Absorption Chillers

Multiple-Effect Absorption Chillers. The efficiency of an absorption chiller can be improved by adding absorption stages to the refrigeration cycle referred to as “effects.” A basic absorption chiller has one refrigeration cycle and multiple-effect absorption chillers have additional refrigeration cycles cascaded on the primary refrigeration cycle to improve chiller efficiency. Each of the cascaded refrigeration cycles uses the waste energy from the previous cycle for operation. Currently the following absorption chillers are available:

- Single-Effect Absorption Chillers
- Double-Effect Absorption Chillers
- Triple-Effect Absorption Chillers

Single-Effect Absorption Chillers. A single-effect absorption chiller is the simplest and the least efficient because it uses only a single refrigeration cycle. With a single-effect absorption chiller, the refrigerant and absorbent only make one pass through the system to absorb heat. However, a single-effect absorption chiller does not need the refrigerant and absorbent to be at high temperature to operate which makes single-effect absorption chillers more suited for indirect-fired systems that are using heat recovery in the form of hot exhaust gases, water, or steam. Single-effect absorption chillers also work best for systems that are using solar and low temperature geothermal hot water or steam to operate. Single-effect absorption chillers are the most common absorption chillers used today due to their simplicity and low initial cost when compared to double- and triple-effect absorption chillers.

Double-Effect Absorption Chillers. Double-effect absorption chillers are more efficient than single-effect absorption chillers because the refrigerant and absorbent make two passes and absorb more heat. Double-effect absorption chillers utilize two refrigeration cycles in tandem with the first driven by the primary heat source and the second driven by waste heat from the first refrigeration cycle. Even though double-effect absorption chillers are more efficient, they are also more expensive and the higher first cost of a double-effect absorption chiller must be offset by the energy savings associated with the increased efficiency over the life of the absorption chiller. For double-effect absorption chillers to operate efficiently they need a higher temperature heat source than is usually available from waste or naturally generated heat. Therefore, double-effect absorption chillers are typically direct fired.

Triple-Effect Absorption Chillers. Triple-effect absorption chillers can further increase operating efficiency above a double-effect absorption chiller. A third refrigeration cycle is used in a triple-effect absorption chiller which means it will need to operate at a higher operating temperature than a double-effect absorption chiller, require more expensive materials to build, and be more complex to operate and maintain. As in the case of the double-effect absorption chiller, the savings that result from the incremental increase in efficiency over a double-effect absorption chiller will need to offset the increased first cost of the triple-effect absorption chiller.

6.8.6 Absorption Chiller Operating Characteristics

Absorption chillers have capacities from about 10 tons to over 1,500 tons of cooling capacity. Their coefficients of performance range from 0.7 to 1.2 and electricity usage from 0.004 to 0.04 kilowatts per ton (kW/ton) of cooling capacity. An electric pump is typically needed by absorption chillers to move the refrigerant and absorbent through the cycle but the amount of energy required to pump the mixture is less than the energy required by the compressor in a mechanical chiller. This is because pumping the liquid mixture through an absorption chiller requires a lot less energy that compressing gas to the same pressure.

6.9 COOLING TOWERS

6.9.1 Cooling Tower Operation

A cooling tower is essentially an evaporative cooler that cools the water coming from the chiller condenser to near the outside wet-bulb air temperature by evaporation and then recycles it back to the condenser to start the cycle again. The heat rejected is comprised of two components:

- Heat extracted from the chilled water.
- Heat added by the compressor.

The compressor adds about 20% to 25% to the cooling load. Cooling towers rated to operate at 78^{o}F wet bulb temperature cool water over a 10^{o}F range from 95^{o}F to 85^{o}F.

Cooling towers are used to dissipate heat from water-cooled refrigeration, air-conditioning, and industrial process systems. Cooling towers can economically cool water to within 5°F to 10°F of the ambient wet bulb temperature or about 35°F lower than air-cooled systems of comparable size. A cooling tower uses a combination of heat and mass transfer to cool water. The water to be cooled is distributed in the tower by spray nozzles, splash bars, or film-type fill in a manner that exposes a very large water surface area to atmospheric air. Circulation of atmospheric air is accomplished by one of the following methods:

- Mechanical Fans
- Natural Convective Air Currents
- Natural Wind Currents
- Induction Effect From Sprays
- Combination Of Methods

The relative heat levels of the water and air cause a portion of the water to evaporate. Since water must absorb heat in order to change from a liquid to a vapor at constant pressure, this heat is taken from the water remaining in the liquid state. In this manner, the heat of vaporization at atmospheric pressure is removed from the circulating water and is transferred to the air stream.

Thermal Performance. The temperature difference between the water entering and leaving the cooling tower is defined as the range. For a system operating in a steady state, the range is the same as the water temperature rise through the load heat exchanger. Accordingly, the range is determined by the heat load and water flow rate, not by the size of capability of the cooling tower.

The difference between the leaving water temperature and the entering air wet bulb temperature is termed the approach to the wet bulb or simply the approach of the cooling tower. The approach is a function of cooling tower capability and a larger cooling tower will produce a closer approach with colder leaving water for a given heat load, flow rate, and entering air condition. Therefore, the amount of heat transferred to the atmosphere by the cooling tower is always equal to the heat load imposed on the tower while the temperature level at which the heat is transferred is determined by the thermal capability of the cooling tower.

The entering air wet bulb temperature affects the thermal performance of a cooling tower. Entering air dry bulb temperature and relative humidity have an insignificant effect on thermal performance but they do affect the rate of water evaporation. The evaporation rate at typical design conditions is approximately one percent of the water flow rate for each 12.6°F of water temperature range. The actual annual evaporation rate is less than the design rate because the sensible component of total heat transfer increases as the entering air temperature decreases. In addition to water loss from evaporation, losses also occur because of liquid carryover into the discharge air stream also referred to as drift and from blowdown required to maintain acceptable water quality.

Thermal Capacity. The thermal capability of any cooling tower may be defined by the following three parameters:

- Entering and leaving water temperatures.
- Entering air wet bulb temperature.
- Water flow rate.

The thermal capability of cooling towers for air conditioning applications is usually stated in terms of nominal tonnage based on a heat dissipation of 15,000 Btu per hour per ton and a water circulation rate of 3 gallons per minute (gpm) per ton cooled from 95°F to 85°F at a 78°F wet bulb temperature. For industrial applications, nominal tonnage ratings are not used and the performance capability of the cooling tower is usually stated in terms of flow rate at specified operating conditions that include entering and leaving water temperature and entering air wet bulb temperature.

6.9.2 Cooling Tower Types

Direct Versus Indirect Evaporative Cooling Towers. The two basic types of evaporative cooling towers are as follows:

- Direct-Contact Evaporative Cooling Tower
- Indirect-Contact Evaporative Cooling Tower

The direct-contact evaporative cooling tower is an open system that cools the hot water from the condenser by direct contact with the atmosphere. By exposing water directly to the cooling atmosphere there is a transfer of heat directly to the air. Spray-filled cooling towers expose water to air without utilizing a heat-transfer medium. Spray-filled cooling towers are the most rudimentary method of exposing water to air. The amount of water surface exposed to the air is dependent on the efficiency of the sprays alone and the time of contact is a function of the elevation and pressure of the water distribution system.

To increase the contact surface as well as time of exposure, a heat-transfer medium called fill is installed below the water distribution system in the path of the air. The two types of fill used in direct-contact evaporative cooling towers are splash type and film type. Splash-type fill maximizes contact area and time by causing the water to cascade through successive elevations of splash bars arranged in staggered rows. Film-type fill achieves the same effect by causing the water to flow in a thin layer over closed-spaced sheets that are arranged vertically.

An indirect-contact evaporative cooling tower on the other hand is a closed system where the hot water from the condenser is circulated through a water-to-air heat exchanger in the cooling tower. Heat from the condenser water is transferred to the atmosphere through the heat exchanger and the condenser water never comes in direct contact with the atmosphere. Indirect-contact towers require a c1osed-circuit heat exchanger that is usually a tubular serpentine coil bundles. The closed-circuit heat exchanger is exposed to air/water cascades similar to the fill of a cooling tower. Some indirect-contact evaporative cooling towers include supplemental film or splash fill sections to augment the external heat-exchange surface area.

Nonmechanical Draft Cooling Towers. Nonmechanical draft towers are aspirated by sprays or density differential, contain no fill, and utilize no mechanical fans for the movement of air. The aspirating effect of the water spray, either vertically or horizontally, induces airflow through the tower in a parallel-flow pattern. Without fans, both entering and leaving air velocities are relatively low for nonmechanical draft towers that make them susceptible to adverse wind effects. As a result, nonmechanical draft towers are normally used to satisfy a low cost requirement when operating temperatures are not critical to the system.

Chimney Cooling Towers. Chimney or hyperbolic towers are the giants of the cooling tower industry. These towers are used primarily for larger power plant installations but are included here for completeness. The heat transfer mode may be counter flow, cross flow, or parallel flow. Air is induced through the tower by the air density differentials that exist between the lighter heat-humidified chimney air and the outside atmosphere. When fills are used they are typically either splash- or film- type.

Mechanical Draft Cooling Towers. The fans on a mechanical draft cooling tower can be installed on either the inlet air side or exit air side. When fans are installed on the inlet air side of a mechanical draft cooling tower it is referred to as a forced draft cooling tower. Similarly, when fans are installed on the exit air side of a mechanical draft cooling tower it is referred to as an induced draft cooling tower. The fans used on mechanical draft cooling towers are typically either centrifugal- or propeller-type fans depending on external pressure needs, permissible sound levels, and energy usage requirements.

The relative direction of air and water through a mechanical draft cooling tower is also used to categorize it. When water is flowing downward and air is flowing upward, the cooling tower is classified as having counterflow heat transfer. Crossflow or horizontal-flow heat transfer occurs when the water is flowing downward and the air is moving horizontally through the cooling tower. All four combinations have been used in mechanical draft cooling towers of various sizes resulting in mechanical draft cooling towers that are:

- Forced-Draft Counterflow
- Induced-Draft Counterflow
- Forced-Draft Crossflow
- Induced-Draft Crossflow

Air can also be single-entry and introduced through one side of tower or double-entry where the air is introduced through in two sides of the tower. A double-entry induced draft crossflow mechanical draft cooling tower.

Mechanical draft cooling towers are also classified as to whether they are factory-assembled or field erected. Factory-assembled mechanical draft cooling towers have the entire tower or a few large components factory-assembled and shipped to the site for final installation. With field-erected cooling towers the tower is completely constructed on site.

Closed-Circuit Mechanical Draft Cooling Towers. Both counterflow- and crossflow-types are used in both forced and induced fan arrangements for closed-circuit mechanical draft cooling towers. The tubular heat exchangers are typically serpentine bundles that are usually arranged for free-gravity internal drainage. Pumps are integrated by the manufacturer to transport water from the lower collection basin to the upper distribution basins or sprays. The internal coils can be fabricated from any of several materials but galvanized steel or copper is commonly used because they are capable of sustaining the required internal pressures.

Closed-circuit mechanical draft cooling towers are increasingly used for heat pump systems. These systems are typically multizone water source heat pumps that have intermediate water heat exchangers coupled to a closed water loop. The closed-circuit mechanical draft cooling tower is installed in this loop in series with a boiler so that heat may be either rejected or added to the system as required to maintain the temperature of the water loop within specified limits.

6.9.3 Cooling Tower Control

Cooling towers must be integrated into the overall central cooling plant control system because cooling towers are an integral part of the refrigeration cycle and the operation of the cooling tower must be matched to chiller operation if the central cooling plant is to operate optimally. Typically the cooling tower, chiller, and condenser pump control must be considered if the overall plant is to be stable and energy-efficient. As discussed previously, there are several types of packaged mechanical-draft cooling towers but the counterflow induced-draft and forced-draft types are the most common for commercial air-conditioning applications. Both are controlled similarly depending on the manufacturer's recommendations. Variable frequency drives are often used to reduce fan power consumption at part-load conditions.

A bypass valve can be used to control condenser water temperature and conserve energy. With centrifugal chillers, the condenser supply water temperature is allowed to "float" as long as the temperature remains above a lower limit. The manufacturer should be consulted regarding the minimum entering condenser water temperature required for satisfactory chiller performance. Minimum condenser water temperatures for centrifugal chillers usually range from 55°F to 65°F. In colder areas that require year-round air-conditioning, cooling towers may require sump heating to prevent freeze-up and continuous full flow over the tower to prevent ice formation. Then the condenser water thermostat would control a hot water or steam valve in sequence with the bypass valve.

CHAPTER VII
HYDRONIC DISTRIBUTION SYSTEMS

7.1 INTRODUCTION

This chapter addresses hydronic distribution systems for central HVAC systems. Hydronics refers to HVAC systems that use water as the heat transfer medium. Hydronic distribution systems cover chilled water, hot water, and steam. This chapter will focus on chilled and hot water distribution systems because these distribution systems are the most common in commercial and institutional building that have central heating and cooling plants. Steam distribution systems are still encountered in older buildings but for the most part steam distribution systems are used in multi-building complexes where a central heating plant serves multiple buildings. Convection terminal units and radiant hydronic heating are also covered in this chapter.

7.2 HOT WATER DISTRIBUTION SYSTEM OPERATION

A simple hot water distribution system is shown in Figure 7-1. As can be seen from Figure 7-1, the boiler provides hot water that is pumped through the hot water supply piping system by the hot water pump. The hot water enters the convection terminal unit which is essentially a water-to-air heat exchanger, passes through the heat exchanger and the exits the convection terminal unit. Cool air enters the convection terminal unit and is warmed by absorbing heat energy from the hot water as the air passes through the water-to-air heat exchanger. The warm air then exits the convection terminal unit and mixes with the existing air in the zone and warms it. The hot water leaves the convection terminal unit at a lower temperature and returns to the boiler through the hot water return piping to be reheated and recirculated.

7.3 CHILLED WATER DISTRIBUTION SYSTEM OPERATION

Figure 7-2 illustrates a simple chilled water distribution system that might be encountered in a commercial or institutional building. As can be seen from Figure 7-2, the chiller is the heart of the chilled water distribution system. The purpose of a chiller is to extract heat from the building by supplying chilled water for circulation through water-to-air heat exchangers located throughout the building. The chilled water piping as well as the piping associated with the cooling tower including pumps and other equipment comprises the chilled water distribution system.

Chilled water in the chiller’s evaporator loop is pumped through the chilled water supply piping by the chilled water supply pump. As will be discussed later in this chapter, the chilled water supply passes through the convection terminal unit that is essentially a water-to-air heat exchanger. As warm air passes through the convection terminal unit the chilled water absorbs heat from the air and cools it. The cool air supplied by the convection terminal unit then mixes with the existing air in the zone to cool the zone. The chilled water is supplied by the chiller and enters the convection terminal unit at about 45^oF, absorbs heat from the warmer air passing through convection terminal unit, and then exits the convection terminal unit around 10^oF warmer at about 55^oF. The water then returns to the chiller through the chilled water return piping to be chilled down to 45^oF again and recirculated.

Figure 7-1 Simple Hot Water Distribution System

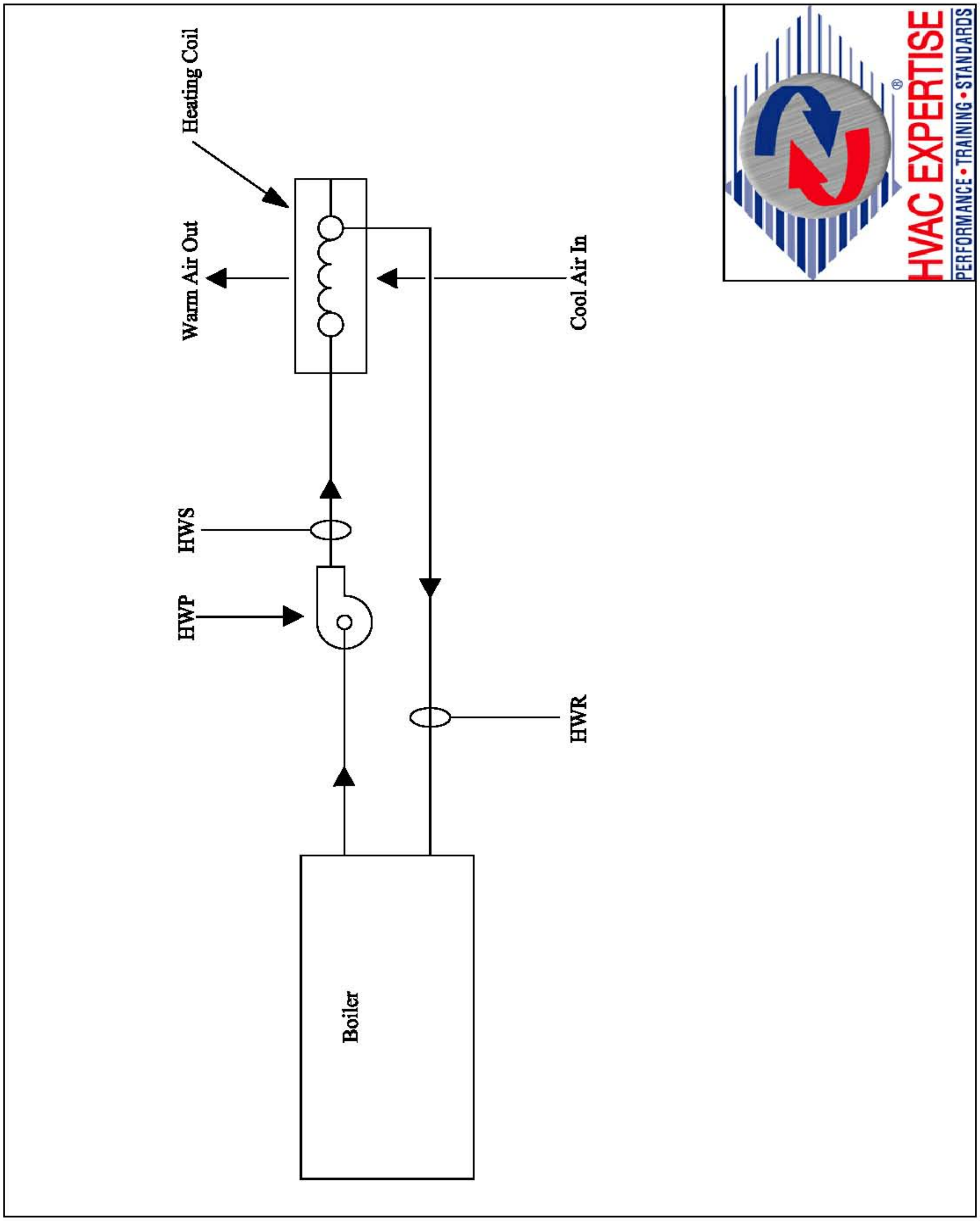
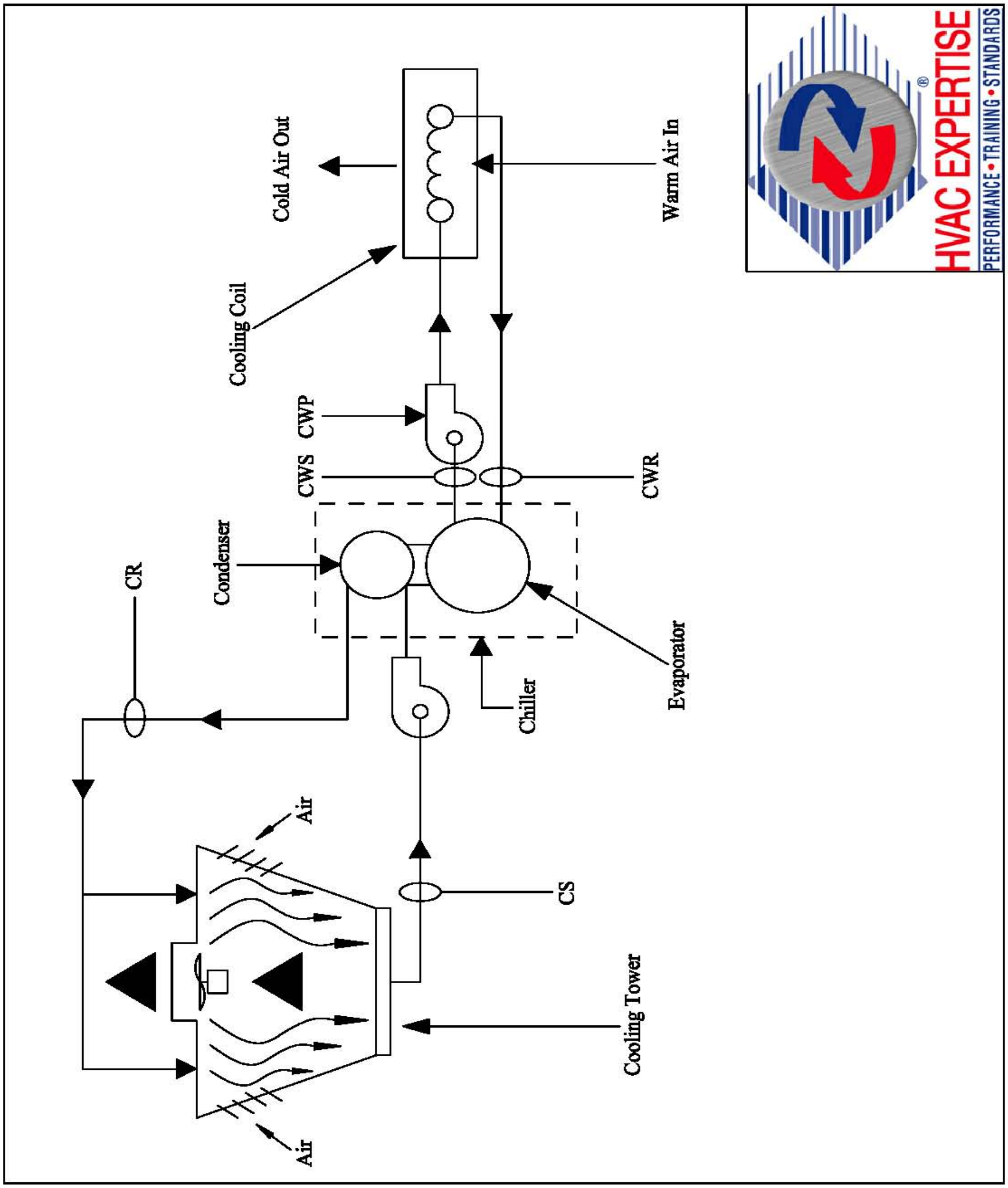


Figure 7-2 Simple Chilled Water Distribution System



There is a second hydronic-piping loop in Figure 7-2 that runs between the condenser and the cooling tower outside the building. This loop is for the condenser water that transports the heat removed from the chiller water as well as the compressor motor and returns it to the cooling tower via the condenser water return piping. The condenser return water is then cooled down from about 95°F to about 85°F by passing it through the cooling tower. The condenser pump pumps the cooler water back to the condenser through the condenser return piping. Once back at the condenser, the entire cycle starts again and the condenser water is recirculated through the condenser loop.

7.4 HYDRONIC DISTRIBUTION SYSTEM OPERATING TEMPERATURE

7.4.1 Operating Temperature Classifications

Hydronic distribution systems can be classified by operating temperature as follows:

- Low Temperature Water System
- Medium Temperature Water System
- High Temperature Water System
- Chilled Water System
- Dual Temperature Water System

Each of these five operating temperature classifications will be discussed in the paragraphs that follow.

7.4.2 Low Temperature Water System

A low-temperature water (LTW) system is a hot water heating system operating within the pressure and temperature limits of the ASME boiler construction code for low pressure heating boilers. The maximum allowable working pressure for low pressure heating boilers is 160 psi with a maximum temperature limitation of 250°F. The usual maximum working pressure for boilers for LTW systems is 30 psi. However, boilers specifically designed, tested, and stamped for higher pressures may frequently be used with working pressures up to 160 psi. Steam-to-water or water-to-water heat exchangers are also sometimes used in low-temperature water systems.

7.4.3 Medium Temperature Water System

A hot water heating system operating at temperatures of 350°F or less with pressure not exceeding 150 psi is classified as a medium temperature water (MTW) system. The usual design supply temperature is approximately 250°F to 325°F with a typical usual pressure rating of 150 psi for boilers and equipment.

7.4.4 High Temperature Water System

High-temperature water (HTW) systems operate at temperatures over 350°F with pressures of about 300 psi. The maximum design supply water temperature is 400°F to 450°F, with a pressure rating of about 3000 psi for boilers and equipment. When designing and installing high-temperature water systems it is important to check the pressure-temperature rating of each component against the design characteristics of the system to ensure that the component has a rating that is sufficient for use on the system.

7.4.5 Chilled Water System

A chilled water (CW) system operates with a usual design supply water temperature of 40°F to 55°F and normally operates at or below a pressure of 125 psi. Antifreeze or brine solutions may be used for systems that require operating temperatures below 40°F to protect against freezing. Chilled water systems that use well water systems may use supply temperatures of 50°F or higher.

7.4.6 Dual Temperature Water System

A dual-temperature water (DTW) system is a hydronic system that circulates both hot and chilled water through a common piping system and terminal heat transfer equipment. These systems are usually operated within the pressure and temperature limits of LTW systems. Typical winter design hot water supply temperatures are about 100°F to 150°F and summer chilled water supply water temperatures between 40°F and 55°F.

7.5 HYDRONIC DISTRIBUTION SYSTEM ARRANGEMENTS

7.5.1 Hydronic Distribution System Arrangements

Common hydronic distribution system arrangements are as follows:

- One Pipe
- Two Pipe
- Three Pipe
- Four Pipe
- Summer-Winter

The following sections will describe and discuss each of these five types of hydronic distribution system arrangements.

7.5.2 One-Pipe Hydronic Distribution System

One-pipe hydronic distribution systems can be classified as either:

- Series Loop
- Diverting Valve

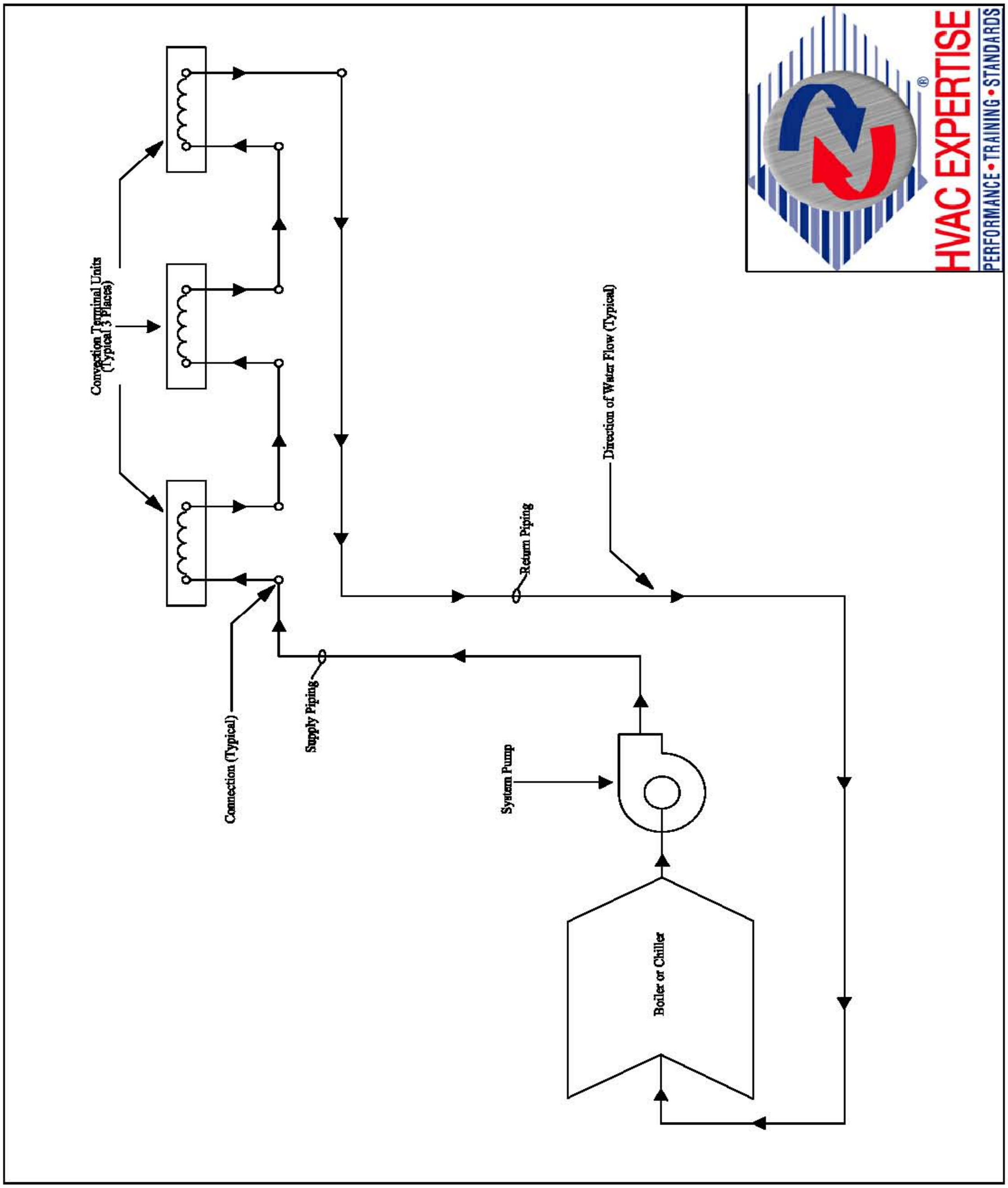
Series Loop. A series loop is a continuous run of pipe from supply connection to return connection. Convection terminal units are a part of the loop as shown in Figure 7-3. Loops may run directly to and from the boilers and chillers or multiple loops may connect to directly to hot or chilled water mains. Water temperature will drop progressively as each convection terminal unit heats or cools the air passing through it. The amount of the temperature change in the water depends on the convection terminal unit heat transfer properties and rate of water flow through it.

A decrease in loop water flow rate will increase the water temperature drop across each convection terminal unit as well as across the entire loop. The water temperature will decrease or increase progressively from the first to the last convection terminal unit in the series loop depending on whether the system is in the heating or cooling mode. The effectiveness of each convection terminal unit gradually decreases from the first to the last unit in the loop. As a result, it is extremely difficult to maintain comfort in separate spaces when they are heated or cooled with a single series loop. Control of output from individual convection terminal units on a series loop is impractical except by controlling the airflow them. Manual dampers can be used on natural convection units or an automatic fan or face-and-bypass damper control can be used on forced air units.

Diverting Valve. With a diverting valve, each convection terminal unit has a supply and a return tee installed on the main. One of the two tees is a special diverting tee that creates a pressure drop in main flow to divert a portion of the main flow to the convection terminal unit. One diverting tee is usually sufficient for up stream convection terminal units. Both a supply and return tee is usually required for down stream units to overcome thermal head. These special tees are proprietary and the manufacturer's literature should be consulted for flow rates and pressure drop data.

One-pipe circuits allow manual or automatic control of flow to individual connected heating units. Simple on-off control rather than flow modulation control is advisable for diverting valve one-pipe hydronic distribution systems because of the relatively low pressure and flow diverted. The loop length and the thermal load imposed on a one-pipe circuit are usually small because of the limitations listed.

Figure 7-3 One-Pipe Hydronic Distribution System



7.5.3 Two-Pipe Hydronic Distribution System

Two-pipe hydronic distribution systems can be classified as one of the following two system types:

- Direct Return
- Reverse Return

Direct Return. Figure 7-4 provides a diagram of a two-pipe direct return hydronic distribution system. As can be seen from Figure 7-4, with a direct return two-pipe hydronic distribution system the return main flow direction is opposite supply main flow. This results in the return water from each unit taking the shortest path back to the boiler or chiller. The direct-return system is popular because less main pipe length is required. However, circuit-balancing valves are usually required on units or subcircuits in order to balance water flow. Operating cost is likely to be higher with a direct return one-pipe hydronic distribution system because of the increased pumping required to overcome the balancing fitting pressure drops for the same water flow rate.

Reverse Return. A diagram of a two-pipe reverse return hydronic distribution system is provided in Figure 7-5. With a reverse-return two-pipe hydronic distribution system the return main flow is the same direction as supply flow. After the last unit is fed, the return main returns all water to the boiler or chiller. Since water flow distance from and to the boiler or chiller is virtually the same through any unit on a reverse-return system, balancing valves are seldom adjusted.

7.5.4 Three-Pipe Hydronic Distribution System

Figure 7-6 provides a diagram of a three-pipe hydronic distribution system. The three-pipe system satisfies the variations in load in each zone by providing independent sources of heating and cooling to each zone. This is accomplished by providing access to both hot and chilled water through the supply piping. Each convection terminal unit contains a single coil that acts as an air-water heat exchanger. A three-way valve at the inlet of the coil controls the amount of hot or chilled water supplied to the convection terminal unit coil. The three-way valve admits the water from either the hot or cold water supply depending on whether the zone served needs to be heated or cooled. The water leaving the coil is carried by a common pipe back to the central heating and cooling plant as shown in the diagram.

Zone control for three-pipe systems is typically achieved by using a special three-way modulating valve that modulates either hot or chilled water supply but does not mix the two. The modulating three-way valve at the inlet to the convection terminal unit is a special design that admits either hot water or cold water to the coil. The hot port on these special three-way valves gradually moves from open to fully closed and the cold port gradually moves from fully closed to open. The valves are constructed so that at mid-range there is an interval in which both ports are completely closed allowing neither hot nor chilled water to flow through the coil.

Figure 7-4 Two-Pipe Hydronic Distribution System (Direct Return)

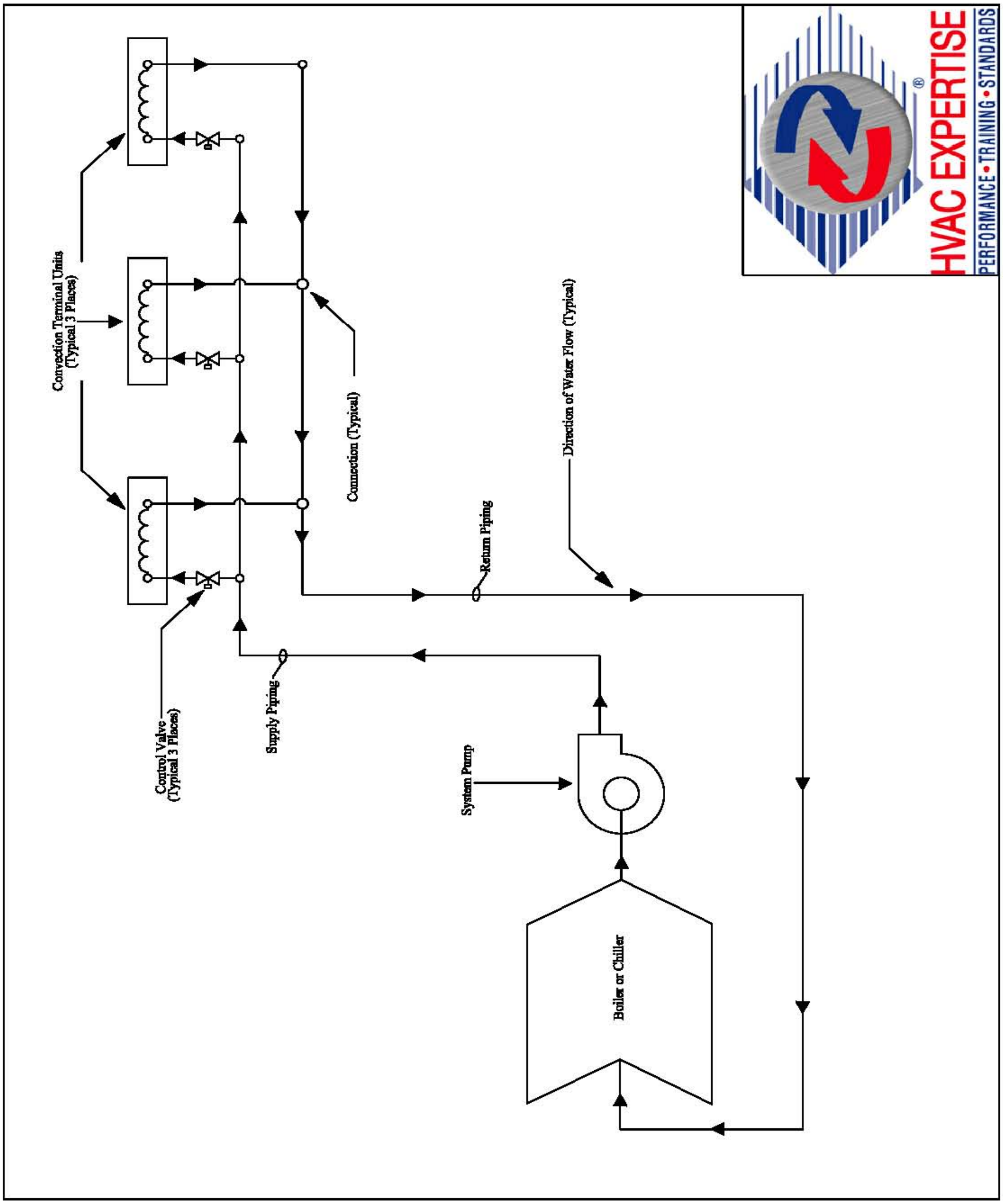


Figure 7-5 Two-Pipe Hydronic Distribution System (Reverse Return)

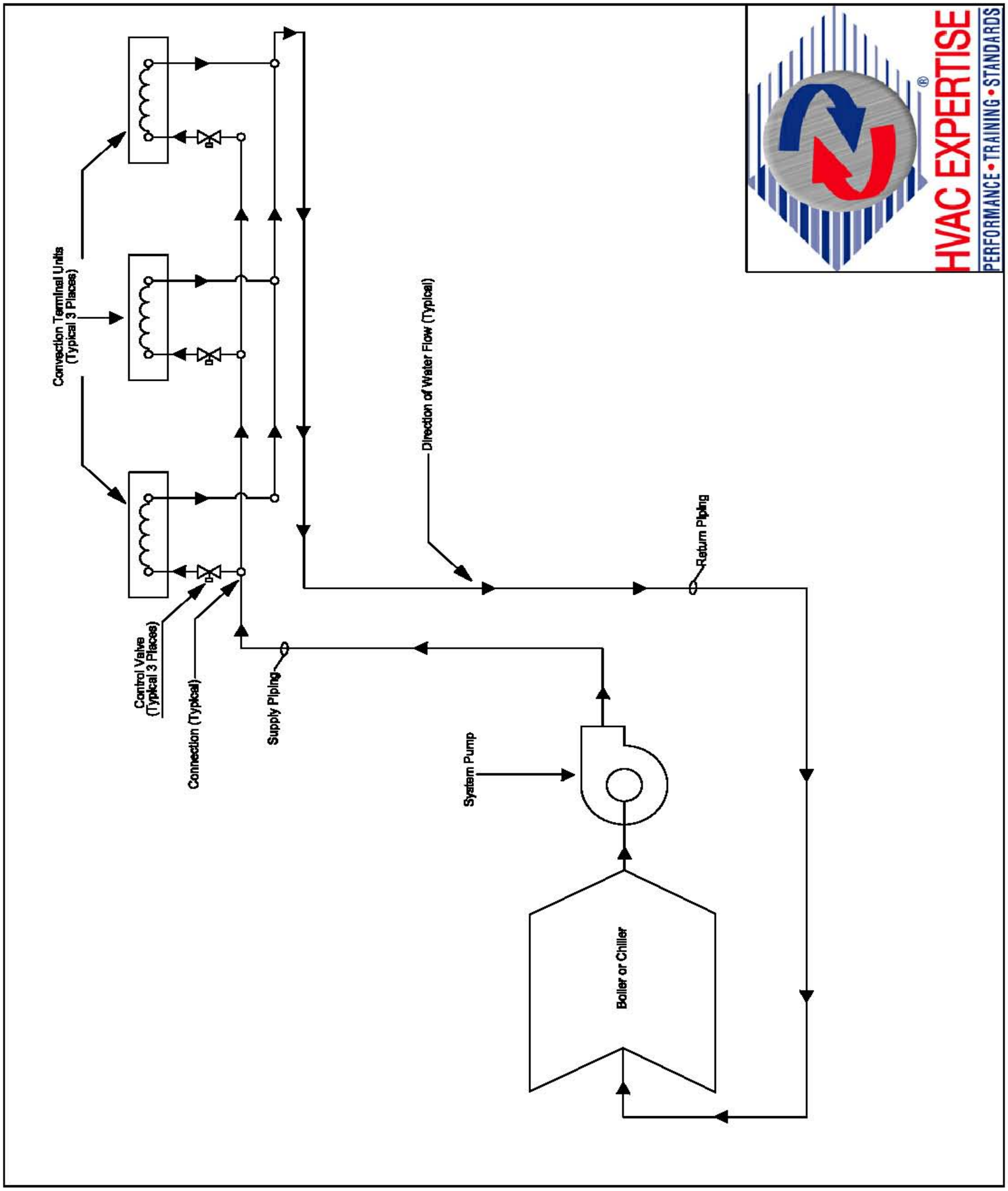
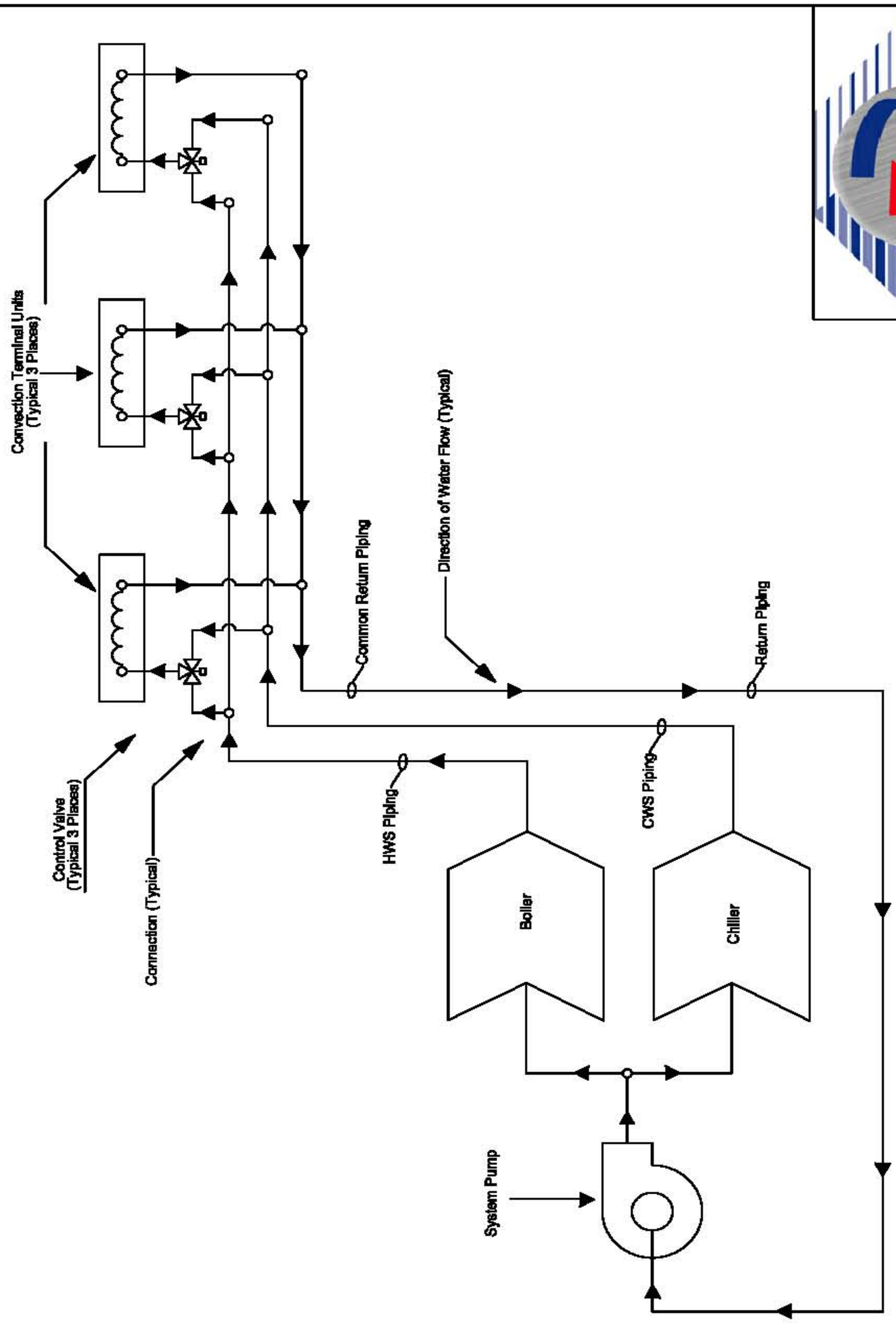


Figure 7-6 Three-Pipe Hydronic Distribution System



During the period between heating and cooling seasons, if both hot and chilled water is available any convection terminal unit can operate anywhere within its range from maximum heating to maximum cooling. With a three-pipe hydronic distribution system, each convection terminal unit operates independently of the other units being served. Due to the operating cost penalty that results from simultaneous heating and cooling loads and the energy wasted by mixing the hot and chilled water in the common return piping, the use of three-pipe hydronic distribution systems under these conditions is not recommended.

7.5.5 Four-Pipe Hydronic Distribution System

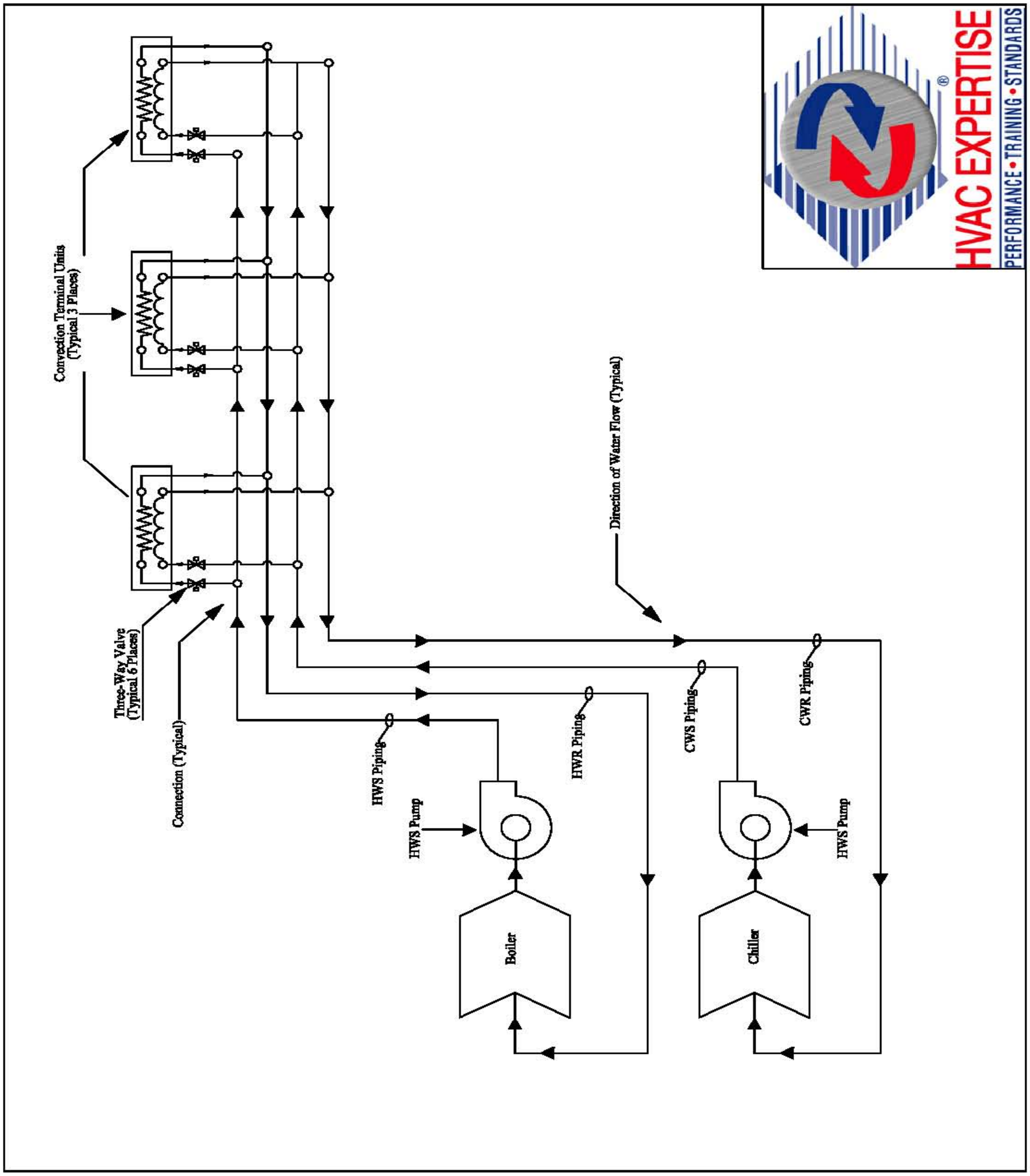
Figure 7-7 provides a diagram of a four-pipe single-coil hydronic distribution system. Four-pipe hydronic distribution systems derive their name from the fact that there are four pipes that serve each convection terminal unit. As can be seen from Figure 7-7, these four pipes provide the following:

- Chilled Water Supply (CWS)
- Chilled Water Return (CWR)
- Hot Water Supply (HWS)
- Hot Water Return (HWR)

A four-pipe hydronic distribution system can address heating and cooling load variations in a zone by using a constant temperature air supply conditioned by hot water or chilled water supplied by the hydronic distribution system.

Single Coil. The convection terminal units used on the four-pipe hydronic distribution system illustrated in Figure 7-7 have only one coil. The three-way mixing valves located at the inlet of the convection terminal unit coil admit water from either the hot or cold water supply as required. At the outlet of the coil, a diverting valve directs the returning water to the appropriate piping system depending on the setting of the mixing valve. This arrangement requires a special three-way mixing valve that was originally developed for three-pipe hydronic systems as described in Section 7.5.4. The mixing valve at the inlet of the single-coil convection terminal unit modulates the hot and chilled water flow but is designed and constructed to be shut off at midrange and never allow the hot and chilled water supplies to mix in the coil. The valve at the convection terminal unit outlet is a two-position diverting valve that allows either the hot or chilled water leaving the coil to return through the appropriate piping system.

Figure 7-7 Four-Pipe Hydronic Distribution System (Single Coil Convection Terminal Units)



Comparing Figures 7-6 and 7-7, it can be seen that a four-pipe hydronic distribution system using single coil convection terminal units is very similar to a three-pipe hydronic distribution system. The main difference between the two systems is the ability in the four-pipe hydronic distribution system to separate the returning hot or chilled water. If the various zones that are served by a four-pipe hydronic distribution system can be providing both heating and cooling simultaneously, a four-pipe hydronic distribution system can provide energy savings over a three-pipe system that mixes hot and chilled return water in a single pipe. Under these conditions, the decision to select a three-pipe or four-pipe for a particular building should be based on a life cycle cost analysis that considers both the first cost of the system and the ongoing operating system operating cost.

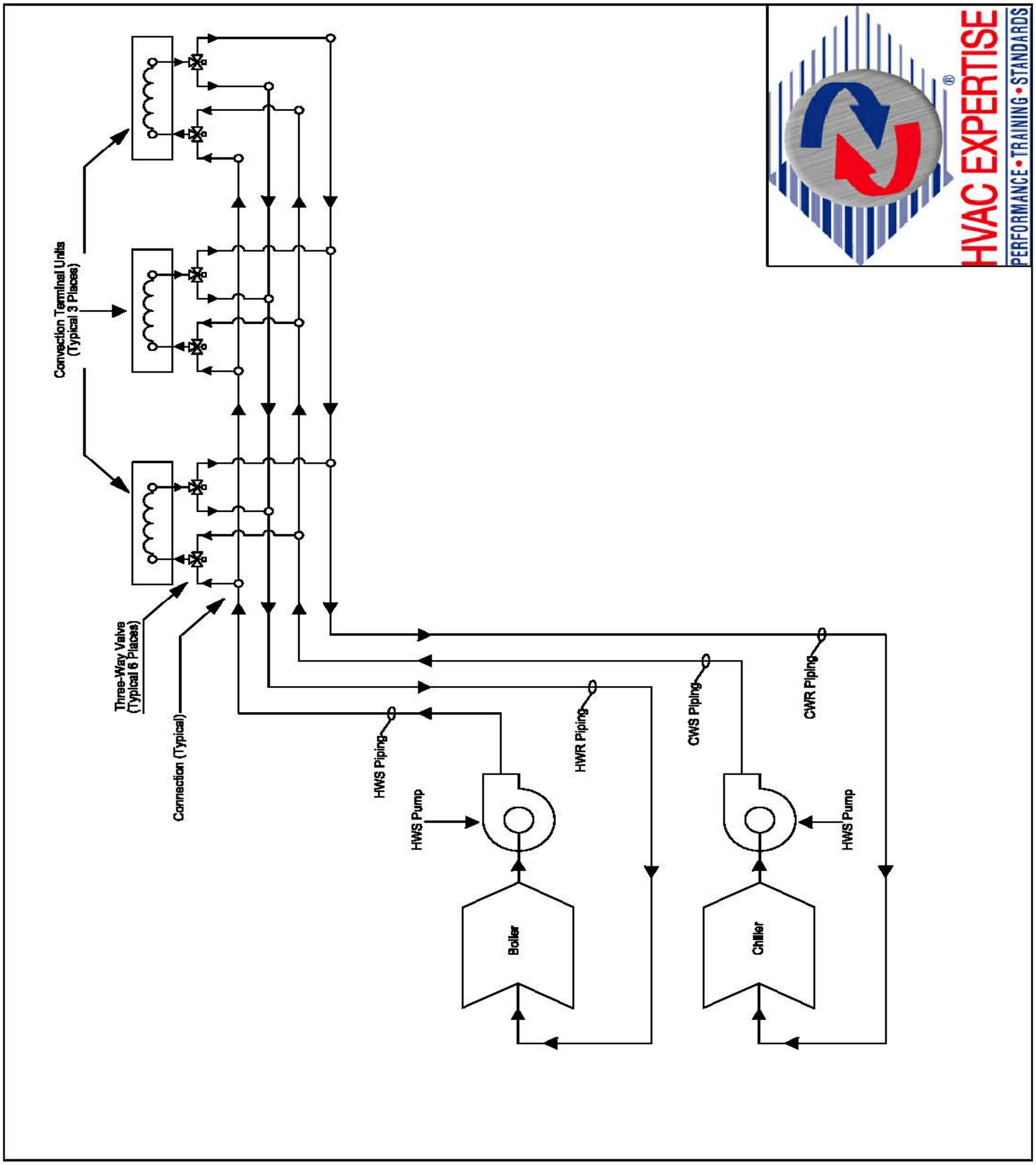
Dual Coil. A four-pipe hydronic distribution system that uses dual coil convection terminal units is illustrated in Figure 7-8. As can be seen from Figure 7-8, the use of dual coil convection terminal units eliminates the need for the special purpose mixing valve and diverting valve needed when a single-coil convection terminal unit. Instead, a control valve in inserted in both the hot and chilled water supply piping on the input to the dual coil convection terminal unit and no diverting valve is required at the outlet.

During peak cooling and heating, the four-pipe system operates like the two-pipe hydronic distribution system discussed in Section 7.5.3 with only the heating or cooling coil in the convection terminal unit operating. During the period between the heating and cooling seasons, any dual coil convection terminal unit on the four-pipe hydronic distribution system can be operated at any capacity level from maximum cooling to maximum heating if both hot and chilled water are available. In addition, each convection terminal unit can be operated independently of any other unit on the system and respond effectively to the space conditioning needs of the zone that it serves.

7.5.6 Summer-Winter Hydronic Distribution System

A summer-winter hydronic distribution system is a variation of the two-pipe hydronic distribution systems shown in Figures 7-4 and 7-5. With a summer-winter hydronic distribution system, the hydronic distribution system is supplied by either the boiler or chiller depending on whether it is heating or cooling season. Hot water is supplied to convection terminal units for heating in the winter and chilled water is supplied to the convection terminal units in the summer for cooling from the building’s central heating and cooling plant. Either manual or automatic changeover valves that are located in the building’s central heating and cooling plant can be used to switch the input to the hydronic distribution system between the hot and chilled water supply. Therefore, Figures 7-4 and 7-5 would be modified by showing a separate boiler or chiller that are both capable of supplying the required hot or chilled water to the system through a common three-way diverting valve. This three-way diverting valve would only allow the hydronic distribution system to be supplied from either the boiler or chiller at any time.

Figure 7-8 Four-Pipe Hydronic Distribution System (Dual Coil Convection Terminal Units)



The advantage of a summer-winter hydronic distribution system is that either the boiler or chiller is operating when needed but they are never both operating at the same time. This results in more economical system operation but may not be acceptable in geographic areas where the need for heating to cooling in the spring or fall is often unpredictable or where these transition periods are long. Summer-winter hydronic distribution systems do not offer the flexibility of other hydronic distribution systems that allow the simultaneous supply of both hot and chilled water. Summer-winter hydronic distribution systems are an economical and widely used piping arrangement utilized in hotels, garden apartments, and other installations where seasonal control is satisfactory.

7.6 MULTI-LOOP HYDRONIC DISTRIBUTION SYSTEMS

Figure 7-9 provides a diagram of a multi-loop hydronic distribution system. As can be seen from Figure 7-9, there is a primary system or loop as it is sometimes called and multiple secondary systems or loops. The secondary hydronic distribution systems in Figure 7-9 are connected directly to the primary hydronic distribution systems. All of the issues with controlling the flow in convection terminal units in the one-pipe hydronic distribution system are present in the primary loop of a multi-loop hydronic distribution system. Flow through secondary loops of multi-loop hydronic distribution systems can be controlled with secondary loop pumps and valves unlike one-pipe hydronic distribution systems.

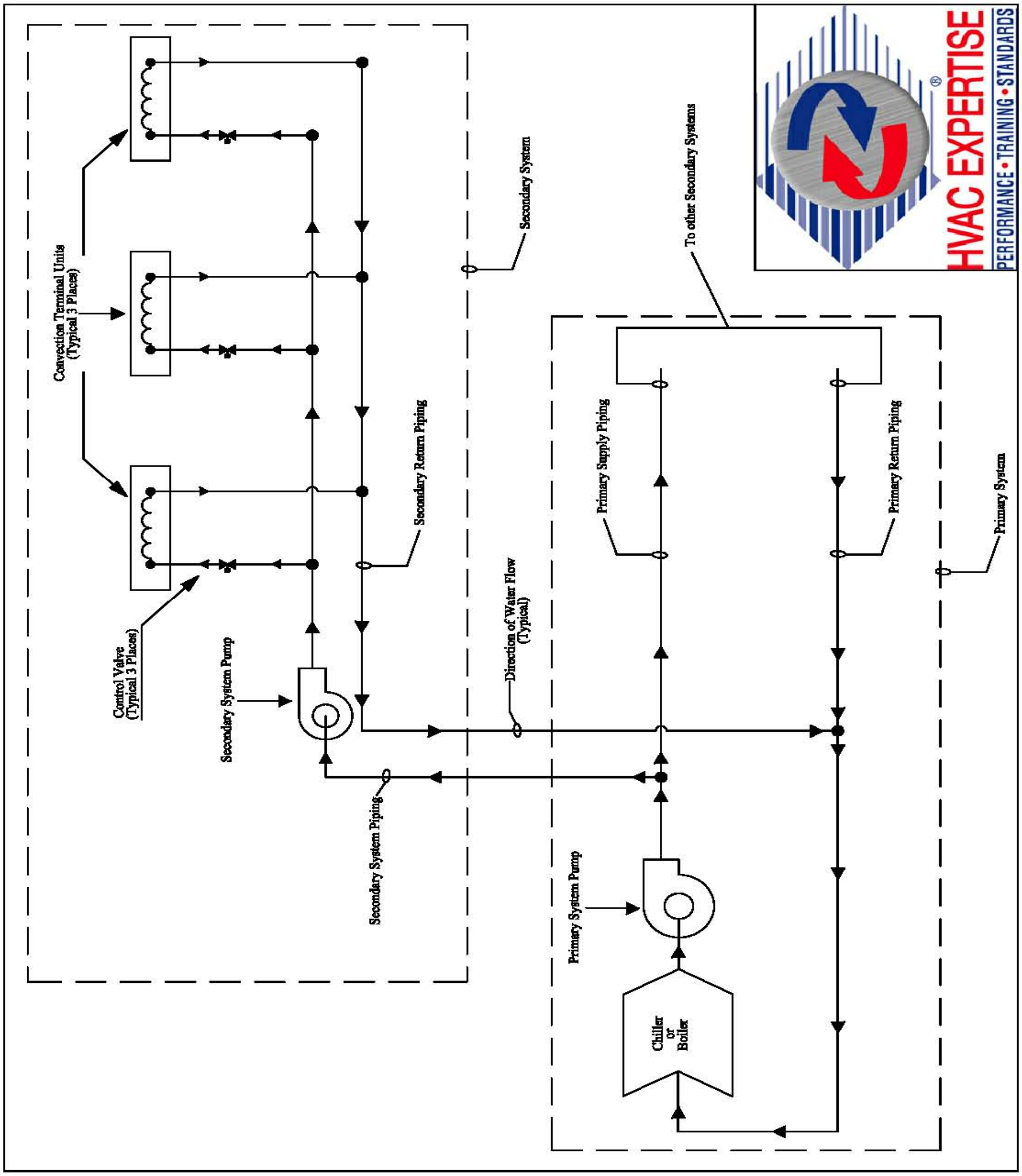
A variation on the secondary system loop being directly connected to the primary system is keeping the water in the two systems completely separated through the use of a water-to-water heat exchanger. Under this arrangement, the hot or chilled water in the primary system is hydraulically separated from the hot of chilled water in the secondary systems or loops. This arrangement makes it impossible for either the primary or secondary systems to be affected by the operation of any secondary other system. In large buildings where several secondary systems are served by a single primary system, there may be advantages to separating the water circuits. In high-rise buildings, the secondary water system should be divided horizontally into two or more zones in order to limit system pressures caused by height.

7.7 HYDRONIC SYSTEM HEAT TRANSFER MODE

7.7.1 Convection Defined.

Convection is one of the three modes of heat transfer along with conduction and radiation. Convection is the transfer of thermal energy between a surface and a fluid passing over it when the two are at different temperatures. In the case of convection terminal units, the surface is the water-to-air heat exchanger in the unit which is often simply referred to as a coil and the air that passes through or over the coil. If chilled water is flowing through the coil and warm air passes over the coil, heat energy from the air will be transferred to the chilled water and the air will be cooled. Similarly, if cool air is passed through the coil and hot water is flowing in the coil, heat energy from the hot water will be transferred to the air and the air will be warmed. The resulting warmed or cooled air will then mix with the air in the zone being served by the convection terminal unit and the temperature will increase or decrease, respectively.

Figure 7-9 Multi-Loop Hydronic Distribution System



7.7.2 Natural Convection

Natural convection is also referred to as free or heat-driven convection. Natural convection relies on changes in the air density to generate airflow through the convection terminal unit. Warm air is less dense than cool air and therefore warm air is pushed upward toward the ceiling by buoyancy carrying the heat energy with it. When this air cools, its density increases and it sinks to the floor. This phenomenon is the basis for the operation of non-fan powered convection terminal units such as a simple cast-iron radiator. Cool air being denser that warm air gathers at the floor level in a space and as it is heated by the radiator it expands and its density increases allowing it to rise and heat the space. The warm radiator results in a constant air flow through it providing both airflow and conditioned air to the space.

7.7.3 Forced Convection

Forced convection is when air is forced to move across the surface of a water-to-air heat exchanger by a means other than the natural forces of buoyancy. This is typically accomplished by the use of a fan in convection terminal units. An example of when a fan is needed in a convection terminal unit is when the unit is needed for cooling. Since cool air is denser than warm air, buoyancy would not result in warm air naturally flowing through a cooling coil in a convection terminal unit located at floor level. As a result, forced convection would be required to move the warm air through the water-to-air heat exchanger to cool the air for reintroduction back into the space.

7.8 CONVECTION TERMINAL UNITS

7.8.1 Convection Terminal Units

There are many types of terminal units that can be used with hydronic distribution systems. These terminal units are water-to-air heat exchangers that heat and cool the zone that they serve through natural or forced convection. Convection terminal units used in commercial and institutional HVAC systems include the following:

- Air-Coil Units
- Fan-Coil Units
- Induction Units
- Unit Ventilators
- Radiators
- Finned-Tube Radiation Heaters
- Valance Units
- Convectors
- Unit Heaters

7.8.2 Air-Coil Units

Air-coil units are simply water-to-air heat exchangers that are usually incorporated into air-handling units, air terminal units such as VAV boxes, or other air distribution equipment. These air-coil units can be served by either a two-pipe or three-pipe hydronic distribution system. With a two-pipe hydronic distribution system, the air-coil unit will usually be either a dedicated heating or cooling coil. With a three-pipe hydronic system, the air-coil unit can be either a heating or cooling coil depending on whether hot water or chilled water is flowing through it. If both hot water and chilled water are available, then the air-coil could switch from being a heating coil to being a cooling coil depending on the needs of the zones that it serves.

7.8.3 Fan-Coil Units

Fan-coil units are self-contained units that include a fan and either one or two water-to-air heat exchangers referred to as coils. The number of coils included in the fan coil unit will depend on whether it is served by a three- or four-pipe water distribution system. When there are two coils, one is used for heating and the other coil is used for cooling. This type of fan-coil unit is sometimes referred to as a four-pipe fan-coil unit. For fan coil units with one coil, that coil is used for both heating and cooling and is often referred to as a three-pipe fan-coil unit. Fan coil units can be mounted either on the wall or on the ceiling of the zone that they serve. Instead of a hydronic heating coil, the fan-coil unit could have an electric heating coil that provides the heating function.

Fan coil units operate by pulling air from the space and conditioning the air by passing it through the coil or coils in the unit and then returning the conditioned air to the space. The air is heated when hot water is being circulated through the operating coil and cooled when chilled water is being circulated through the operating coil. The air returned to the zone and mixes with the existing air to maintain the desired temperature.

A local thermostat typically regulates the zone temperature by controlling both the fan and the amount of hot or chilled water that circulates through the coil. The amount of hot or chilled water circulating through the coil is modulated by a control a valve that is integral to the fan-coil unit. Fan control by the thermostat is typically only on and off but there fan-coil units typically have manual fan speed controls that allow the occupant to select between two or more fan speeds.

Fan-coil units can also include an outside air intake and damper that allows the introduction of outside air into the space for indoor air quality. Outside air intakes are common in wall-mounted fan-coil units that serve a zone in an enclosed space that has no other effective means of introducing outside air into the space. Ceiling-mounted and interior wall-mounted fan-coil units can also have ducted outside air supplied to them.

7.8.4 Induction Units

An induction unit is essentially a fan-coil unit that injects air from the space into the unit using which velocity nozzles instead of a fan. The high-velocity air in turn induces a secondary air flow through the unit which is where the unit gets its name. The induced air then conditioned by flowing through the coil or coils as it does in the fan-coil unit discussed in the previous section. Induction units are very seldom used and almost never used in new construction. Other than the high-velocity air supply through nozzles, induction units operate the same as fan-coil units.

7.8.5 Unit Ventilators

Unit ventilators are forced convection units that use a fan to force air through the unit and include water-to-air heat exchangers for zone heating, cooling, or both. Unit ventilators also include an outside air supply and dampers to control the amount of outside air introduced into the zone for ventilation purposes as well as free cooling.

7.8.6 Radiators

Radiators are simple water-to-air heat exchangers that are used exclusively for space heating. Radiators rely solely on natural convection for heating.

7.8.7 Finned-Tube Radiation Heaters

Finned-tube radiation heaters rely on natural convection just like traditional radiators but are more efficient because they have a greater surface area for heat transfer.

7.8.8 Valance Units

Valance units are finned-tube water-to-air heat exchangers that are either installed high on a wall for cooling or low on the wall for heating. Valance units normally do not include a fan and rely on the natural convection to move air through them so that it can be conditioned when passing over the finned-tube heat exchanger. As a result, valance units only have one coil and are either dedicated to heating or cooling. Valance units are used in building renovation where there is limited space for equipment in the zone requiring additional heating and cooling.

Valance units are most commonly used for heating and are sometimes referred to as baseboard radiators. Valance units look a lot like electric resistance baseboard heaters. Located close to the floor, these units use natural convection to draw cool air from the space at floor level, condition it as it moves through the finned-tube radiator, and then supplies the conditioned air to the space through the top of the unit.

7.8.9 Convectors

A convector is a high-capacity water-to-air heat exchanger that includes one or more finned-tube heat exchangers enclosed in housing that allows air from the space to be drawn in from the bottom, heated by passing through the finned-tube heat exchangers, and then reintroduced to the space through the top of the unit. Convectors sometimes include fans but normally rely on natural airflow through the unit by induced natural convection to condition the space.

7.8.10 Unit Heaters

Unit heaters are used in unfinished areas such as truck docks, warehouses, and other similar locations to provide heat. Unit heaters can also channel their heat output directly downward which allows them to be used in small spaces needing a large amount of heat such as building entrances where doors are opened frequently. Unit heaters consist of a fan and coil packaged in a single housing that is served by the hot water distribution system. Unit heaters are used in locations where there is a need for high heat output but no cooling is required.

7.9 HYDRONIC RADIANT HEAT

The third mode of heat transfer is radiation. Radiation differs from conduction and convection in that no contact is required between the heat source and the air or object that is being heated. Hydronic systems can be used to provide radiant heat to a zone by installing hydronic piping in the floor, walls, ceiling, or a combination of these surfaces and circulating hot water through the piping system. Heat is then radiated from the surfaces and warms the area that it serves. Radiant heating can also be accomplished by embedding electric resistance cables in building surfaces as well.

Where it is not possible to embed the hot water piping in the building surfaces, radiant panels can be mounted on building surfaces to provide radiant heat. Radiant panels are most often installed on ceilings and these panels are normally used in areas as supplemental heating.

CHAPTER VIII
AIR DISTRIBUTION SYSTEMS

8.1 INTRODUCTION

Air distribution systems and the components that make them up are covered in this chapter. This chapter starts by discussing the purpose of an air distribution system in a building and the major components that comprise an air distribution system. This is followed by sections on fans and fan operation, air handling units, air ducts and plenums, variable-air-volume air terminal units, air outlets and inlets, and air cleaning devices. This chapter also covers the dynamics of air distribution system operation including the use of variable frequency drives on fans to improve air distribution system operation and efficiency.

8.2 AIR DISTRIBUTION SYSTEM PURPOSE

The purpose of air distribution systems is essentially the same as a hydronic distribution systems covered in Chapter VII. The purpose of a hydronic distribution system is to deliver chilled and hot water to cooling and heating coils throughout the building to condition air that is delivered to the zones served. The purpose of an air distribution system is the same except instead of delivering chilled and hot water, the air distribution system provides closed system for delivering conditioned air to zones, recovering air from zones, providing outside air for mixing with return air to be reconditioned, and exhausting recovered air to the outdoors as required. Without an air distribution system there would be no way of controlling the airflow and temperature in zones throughout the building. Properly designed, installed, and maintained air distribution systems help provide a healthy, comfortable, and productive environment for building occupants.

8.3 AIR DISTRIBUTION SYSTEM COMPONENTS

Air distribution systems are comprised of a number of components that help maintain a healthy, comfortable, and productive environment for occupants. The air distribution system is not just the air ducts that direct the air to zones throughout the building. The air distribution system includes fans that move the air and ensure that it is delivered to the zones served at the right airflow as well as air cleaners that remove both particulate and biological contaminants from the air stream. Thermal conditioners in the form of heat exchangers that are typically referred to as coils that remove or add heat to the supply air are also part of the air distribution system when air is conditioned prior to delivery to the zone served. In addition, many other devices such as humidifiers and dehumidifiers that add or remove water from the supply air stream are also part of the air distribution system when required.

8.4 FANS

8.4.1 Fan Purpose

The purpose of a fan is to move air through the air distribution system so that it can be delivered to a zone at a given flow rate. In this respect, a fan can be thought of as a pump and the pressure determines the rate at which air is pumped by the fan. By creating a pressure differential, air moves through the air distribution system. In other words, the greater the pressure differential that the fan creates, the greater the volume of airflow through the system. The airflow through a fan is determined by the resistance to flow which is also referred to as static pressure.

8.4.2 Fan Categories

There are two basic types of fans used in HVAC applications. These two types of fans are categorized according to the direction of airflow through the fan and are as follows:

- Axial Fans
- Centrifugal Fans

The following paragraphs will discuss each of these fan categories and the common types of fans that make up the category.

8.4.3 Axial Fans

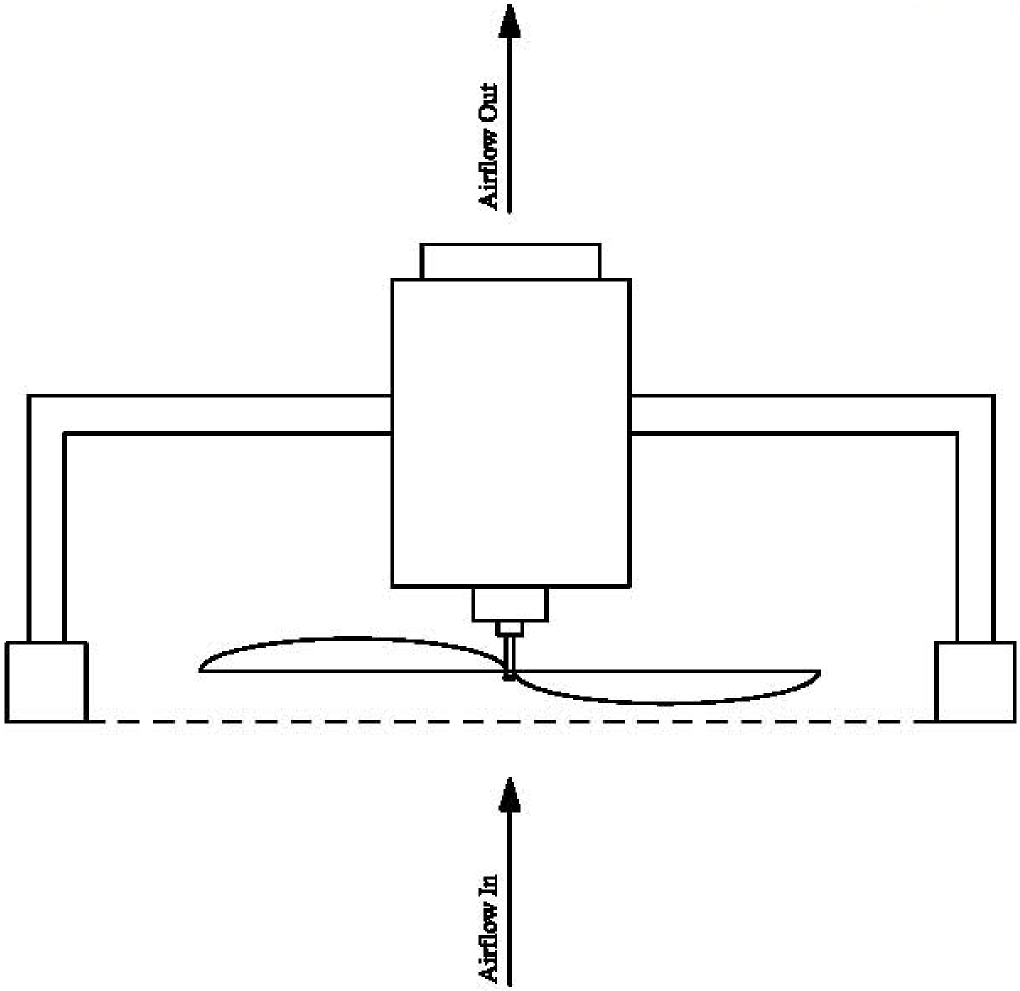
Axial fans get their name from the fact that the airflow through the fan is along the axis of the fan body and perpendicular to the impeller or blade. Axial flow fans are typically used in applications that require high volumes of airflow and low static pressure. An example of an application for an axial flow fan would be an exhaust fan. Axial fans also have the ability to reverse airflow by changing the direction of their rotation which centrifugal fans are not able to do.

Axial fans can be further divided into the following three fan types:

- Propeller Fans
- Tube-Axial Fans
- Vane-Axial Fans

Propeller Fans. Propeller fans get their name from the fact that their impeller looks like an airplane propeller. A diagram of a propeller fan is shown in Figure 8-1. Propeller fans are typically found in applications where a large volume of air needs to be moved against little or no static pressure. Propeller fans are commonly found in residential applications such as a simple box fan or an attic fan used for ventilating or cooling a room or the entire home. In commercial, industrial, and institutional applications, propeller fans are most often used as exhaust fans and can be either roof or wall mounted. Propeller fans are also sometimes used for ventilating unconditioned buildings such as warehouses.

Figure 8-1 Axial-Flow Fan: Propeller Type



Tube-Axial Fans. Tube axial fans encase their impeller in a cylindrical enclosure as shown in Figure 8-2. By placing the impeller in a cylindrical enclosure that guides the air through the fan, tube-axial fans are able to deliver higher airflows against higher static pressures than simple propeller fans more efficiently.

Vane-Axial Fans. A diagram of a vane-axial fan is shown in Figure 8-3. Vane axial fans differ from tube-axial fans in that they have a set of vanes located either at the inlet or outlet of the fan to guide the air through the fan. Due to their design, vane-axial fans can be used in applications that require airflow delivered at higher pressures through supply ducts. Vane-axial fans are not as efficient as propeller fans but tend to be the most efficient fans available for HVAC air-handling units (AHU) with efficiencies in the upper 80 percents largely because the direction of the airflow is little changed as it passes through the fan.

Axial Fan Blade Pitch. The pitch of axial-flow fan blades can be:

- Fixed
- Adjustable
- Variable

With fixed-pitch blades, the fan blade pitch cannot be changed. However, adjustable-pitch blades allow the user to manually adjust the blade pitch to set the fan's supply airflow and not penalize efficiency. Adjustable-pitch blades can be a useful feature for building commissioning. Variable-pitch blades allow the flan blade pitch to be varied during operation by pneumatic or electric actuators that allows them to provide efficient airflow without changing the speed of the fan. However, the mechanism that varies the blade pitch must be maintained to ensure proper operation over time.

8.4.4 Centrifugal Fans

Centrifugal fans are similar built and operate similar to centrifugal pumps with the fan impeller enclosed in a casing. Unlike an axial fan where the air stream passes straight through the fan, the air stream makes a right angle from where it enters the fan. Centrifugal fans get their name from the fact that the air is spun around by the impeller and ejected by centrifugal action. Centrifugal fans are less efficient than axial fans with efficiencies up to about 80 percent for backward-curved blade centrifugal fans compared to up to 90 percent efficiency for axial fans. However, centrifugal fans are typically quieter than axial fans which is important in HVAC applications but have more inertia and require greater motor starting torque than axial flow fans.

Centrifugal fans are further classified by the their impeller blade construction as follows:

- Backward Curved (Airfoil) Blade
- Radial (Straight) Blade
- Forward-Curved Blade

Figure 8-2 Axial-Flow Fan: Tube-Axial Type

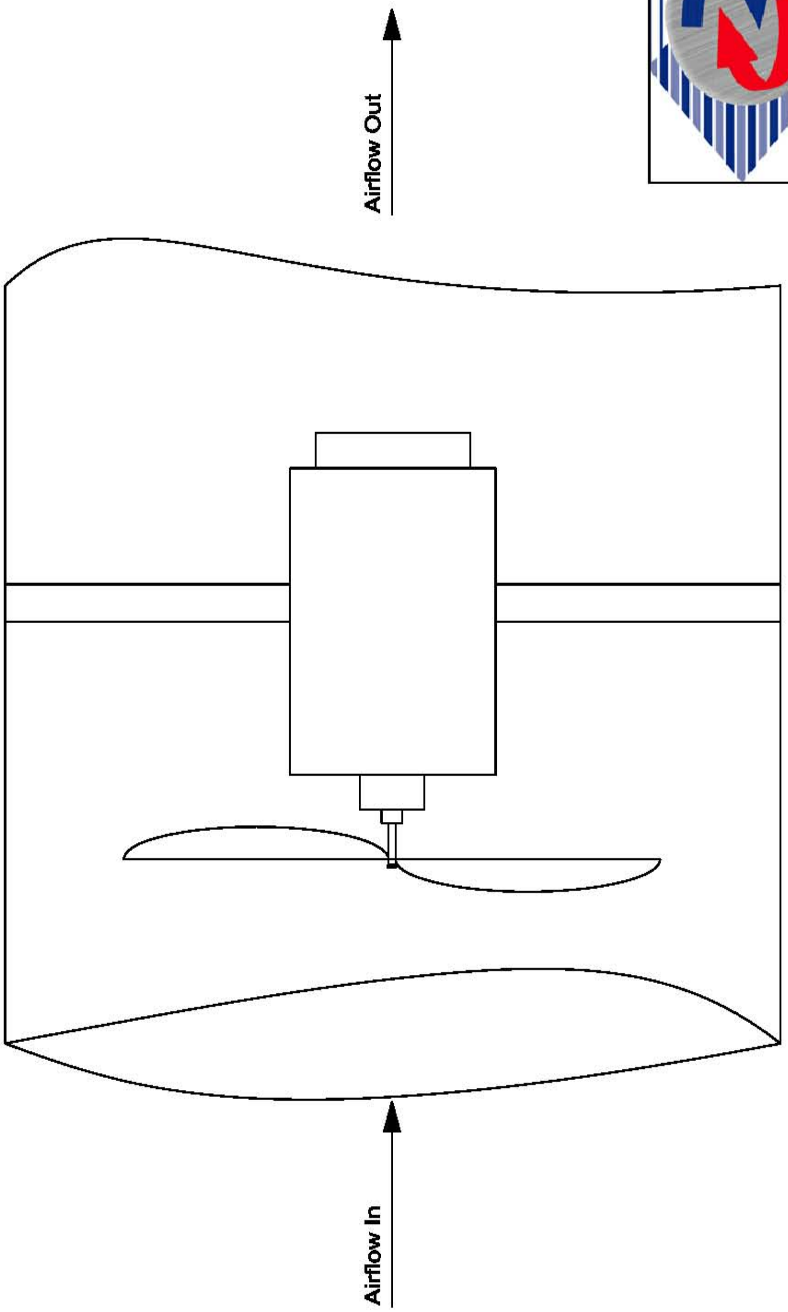
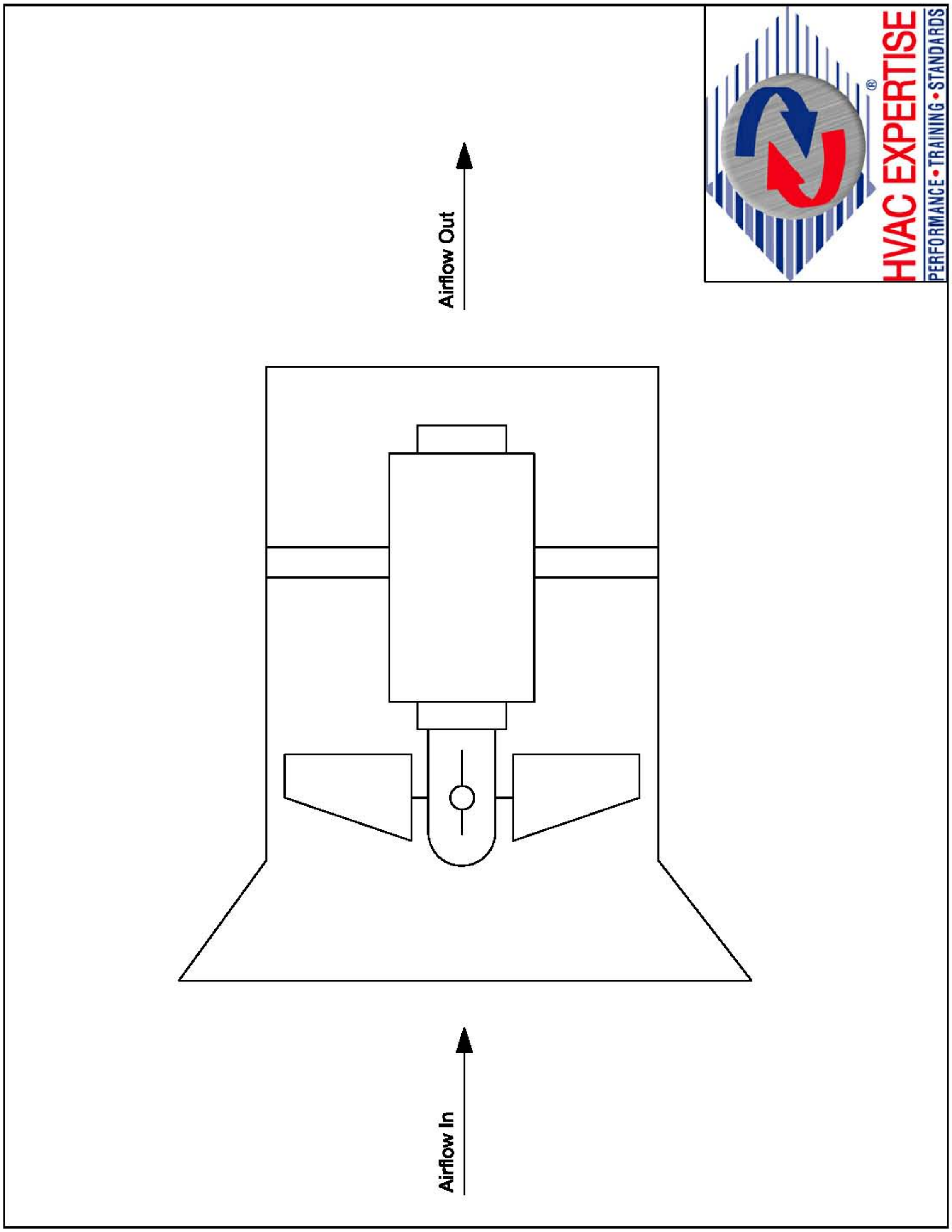


Figure 8-3 Axial-Flow Fan: Vane-Axial Type



Backward Curved (Airfoil) Blade. Backward curved or airfoil blade centrifugal fans have blades that are curved backward and look like an airplane wing. Backward-curved blade centrifugal fans are the most efficient blade configuration and are commonly used in commercial and institutional HVAC systems. Figure 8-4 provides a diagram of a backward curved blade centrifugal fan.

Radial (Straight) Blade. Centrifugal or straight blade centrifugal fans are most often found in manufacturing and industrial operations and used in exhaust and ventilation applications. A diagram of a radial blade centrifugal fan is provided in Figure 8-5. The main advantage of a radial blade impeller over backward and forward blade impellers is that a radial blade impeller will allow small airborne particulates such as sawdust and metal shavings to pass through the fan in the air stream. Radial blade centrifugal fans are not used in commercial and institutional HVAC systems because they are not as efficient as backward curved blade centrifugal fans and their ability to pass small airborne particulates found in the air stream is not an advantage for HVAC systems. Radial blade centrifugal fans have typical efficiencies of around 50 to 60 percent.

Forward Curved Blade. Forward curved blade centrifugal fans are the least efficient type of centrifugal fan but they can be built smaller and less expensively than backward curved blade centrifugal fans. Forward curved blade centrifugal fans are used primarily in smaller unitary HVAC equipment. A diagram of a forward curved blade centrifugal fan is provided in Figure 8-6.

8.4.5 Fan Operation

Figure 8-7 illustrates a fan curve for a typical centrifugal fan with backward curved blades. A fan curve provides the unique operating characteristics for a fan that is running at a given speed or revolutions per minute (rpm). The fan curve describes the relationship graphically between airflow and static pressure for a particular fan running at a given speed. Fan manufacturers determine fan curves by testing the fan under controlled conditions.

Given the fan curve for a particular speed, the fans operating point for a specified airflow or static pressure can be determined. For example, given a static pressure, the resulting airflow can be read from the fan curve by drawing a horizontal line from the static pressure on the vertical axis to the intersection of the fan curve. From the intersection, draw a vertical line and read the resulting airflow from the horizontal axis. The static pressure for a given airflow can also be determined from the fan curve by reversing the above process.

From Figure 8-7, it can be seen that if the fan is being driven at 1000 rpm and has a static pressure of 2.5 in. wg at its outlet, the airflow through the fan will be 24000 cfm. If the static pressure at the outlet of the fan increases to 3.0 in. wg at the outlet the airflow drops to about 22000 cfm. Similarly, the airflow will increase to 25500 cfm if the static pressure at the outlet of the fan decreases to 2.0 in. wg at the outlet.

Also shown in Figure 8-7 is the fan brake horsepower (BHp) curve. This curve provides brake horsepower as a function of cfm for the fan. At an operating point of 24000 cfm and 2.5 in. wg, the fan's required brake horsepower at 1000 rpm is 14.25.

Figure 8-4 Centrifugal Fan: Backward Curve (Airfoil) Blade

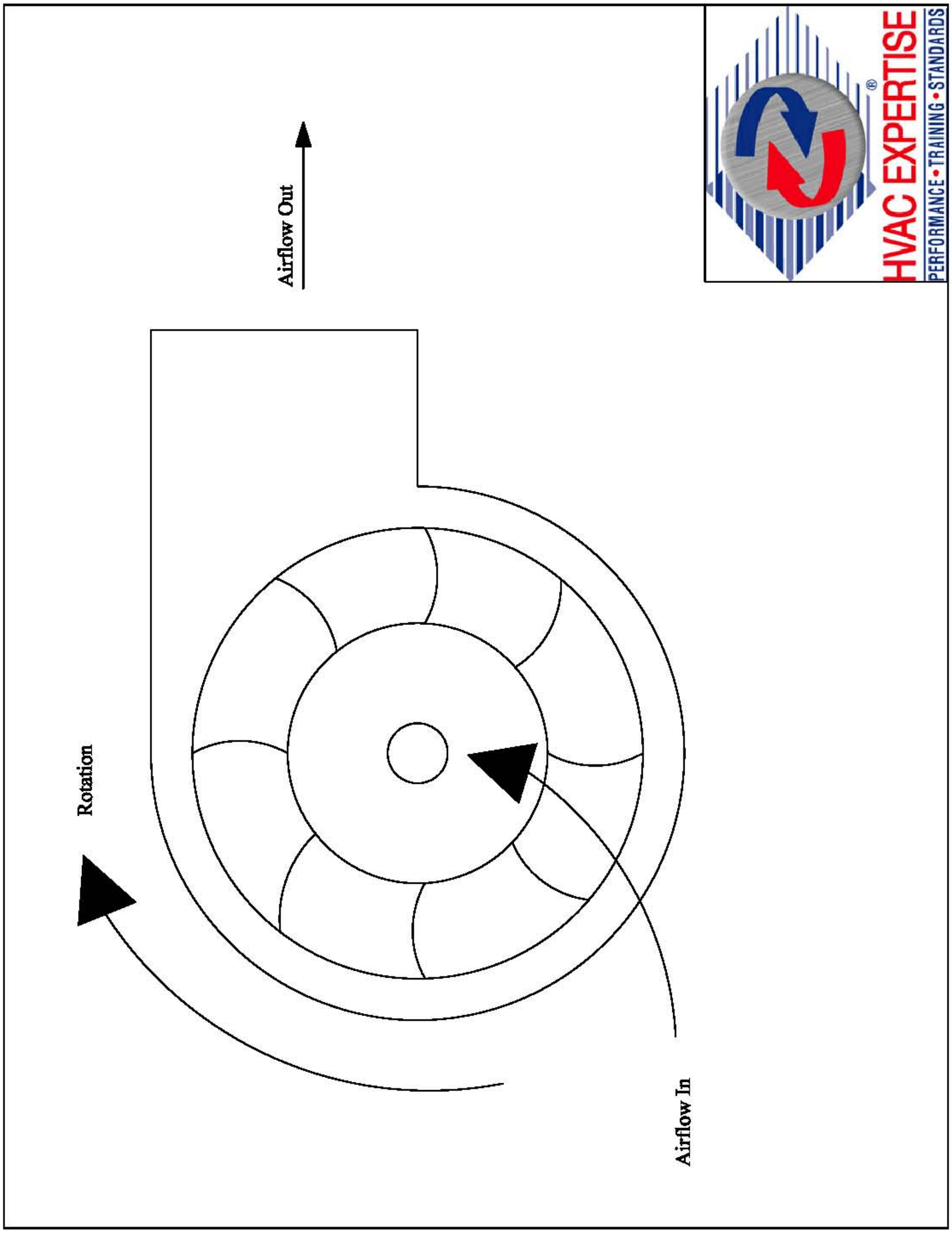


Figure 8-5 Centrifugal Fan: Radial (Straight) Blade

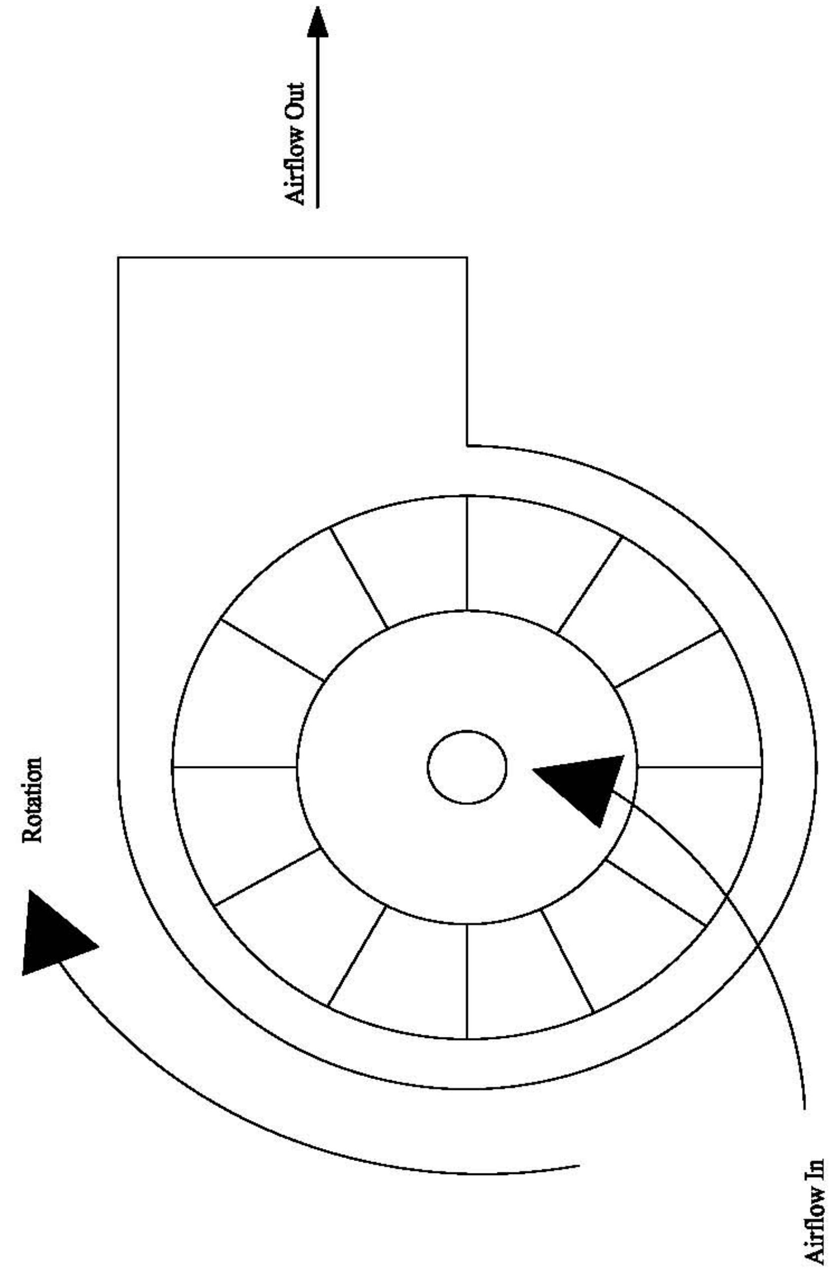


Figure 8-6 Centrifugal Fan: Forward Curved Blade

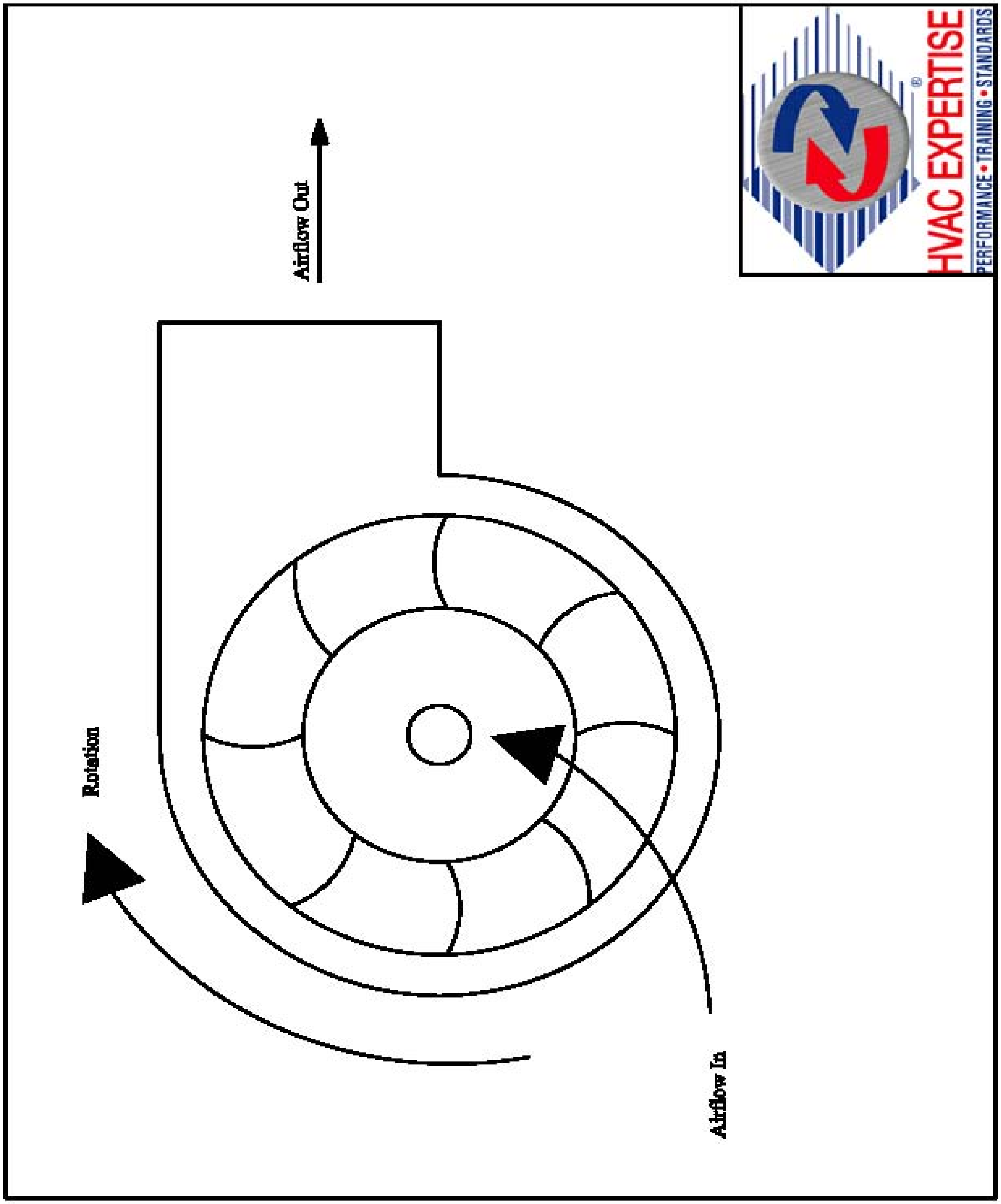
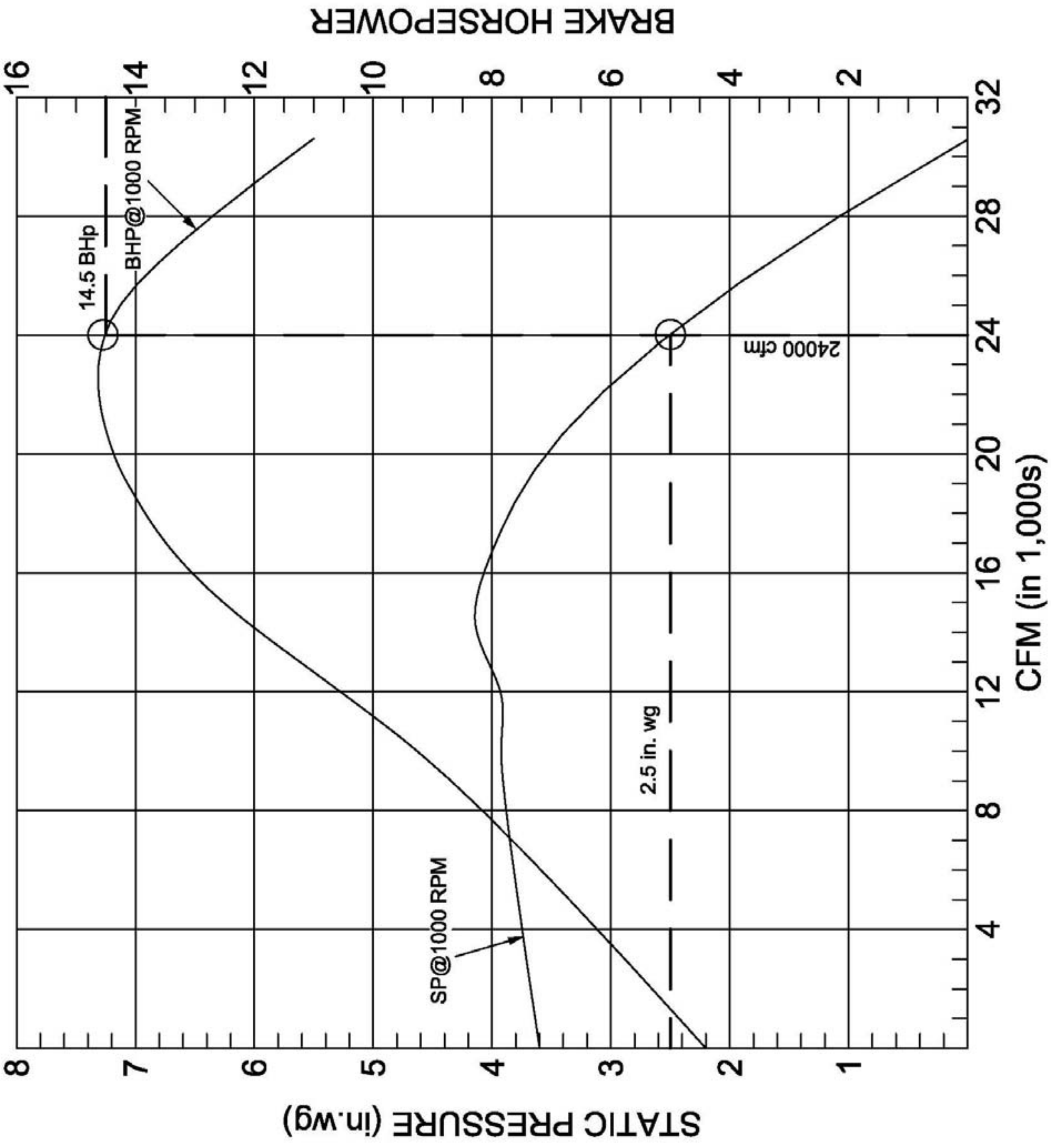


Figure 8-7 Fan Curve for Typical Centrifugal Fan: Backward Curved Blade



8.4.6 Varying Fan Speed

A fan curve illustrates the relationship between static pressure and airflow for a fan at a given speed. At a constant speed of 1000 rpm, the fan's operating point will move along the fan curve with airflow and static pressure changing as shown in Figure 8-7. In order to achieve a static pressure and airflow different from those defined by the 1000 rpm fan curve, the speed of the fan must be changed.

Changing the fan speed results in a new fan curve that provides a new set of unique relationships between static pressure and airflow for the fan at the new speed. Allowing fan speed to vary results in a family of fan curves as shown in Figure 8-8. From Figure 8-8, it can be seen that by increasing the fan speed from 1000 rpm to 1050 rpm and keeping the static pressure constant at 2.5 in. wg in., airflow increases from 24000 cfm to about 26000 cfm. Similarly, decreasing the fan speed to 950 rpm from 1000 rpm for a static pressure of 2.5 in. wg results in the airflow from the fan decreasing from 24000 cfm to 26000 cfm. In general, for a constant static pressure, increasing the fan speed increases airflow and decreasing static pressure decreases airflow.

Similarly, by holding airflow constant at 24000 cfm and increasing speed from 1000 rpm to 1050 rpm results in an increase in static pressure for the fan from 2.5 in. wg to 3.2 in. wg. Decreasing fan speed from 1000 rpm down to 950 rpm at 24000 cfm results in a decrease in static pressure from 2.5 in. wg to about 1.8 in. wg in Figure 8-8. In general, for a constant airflow, increasing fan speed increases static pressure and decreasing fan speed decreases static pressure.

8.4.7 Fan Laws

Fan laws express the relationship between airflow, static pressure, and brake horsepower as a function of fan speed for a fan.

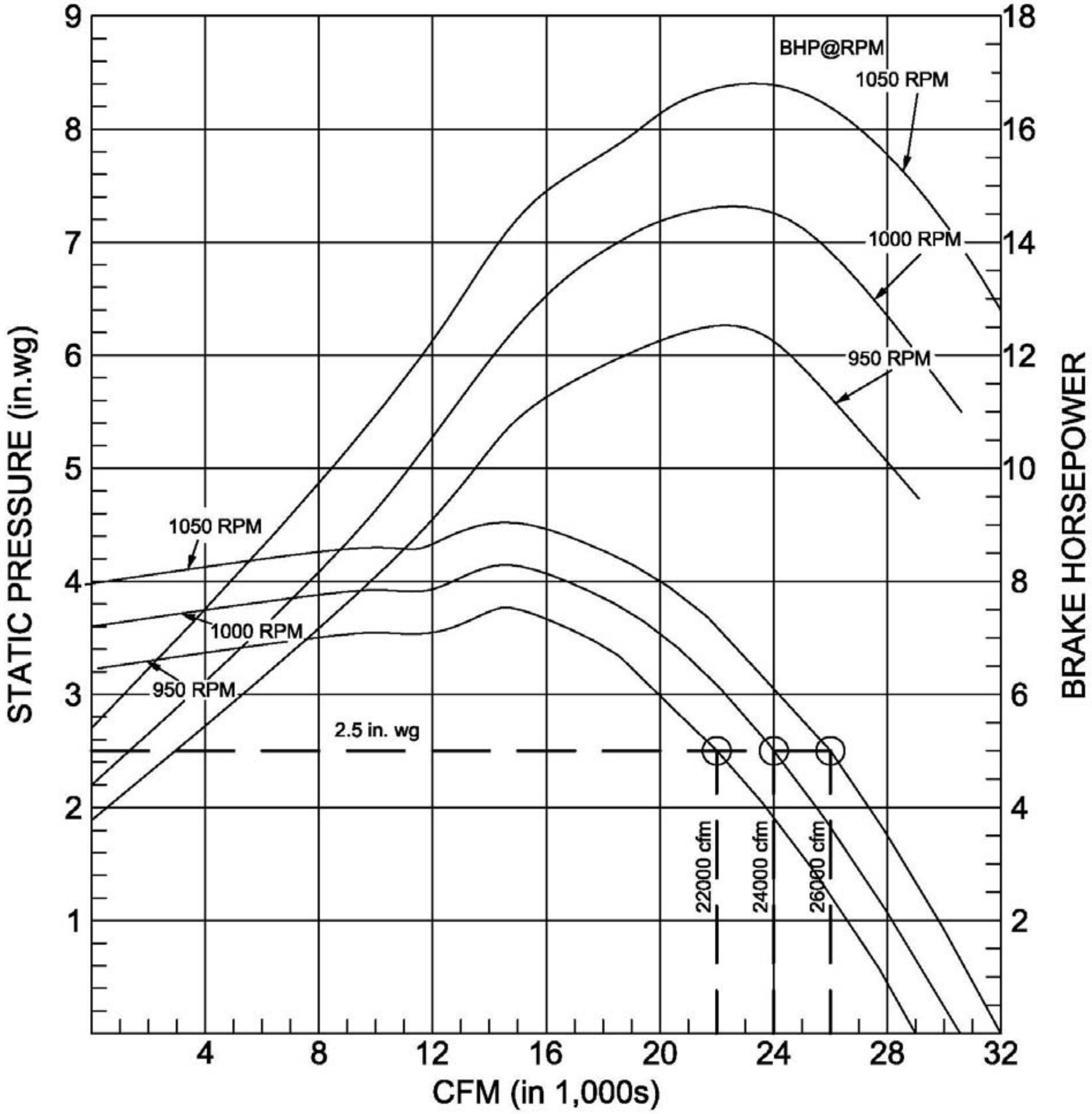
$$\frac{\mathrm{cfm}_1}{\mathrm{cfm}_2} = \frac{\mathrm{rpm}_1}{\mathrm{rpm}_2}$$

$$\frac{\mathrm{SP}_1}{\mathrm{SP}_2} = \left(\frac{\mathrm{rpm}_1}{\mathrm{rpm}_2}\right)^2$$

$$\frac{\mathrm{Bhp}_1}{\mathrm{Bhp}_2} = \left(\frac{\mathrm{rpm}_1}{\mathrm{rpm}_2}\right)^3$$

In the previous section, the fan curves were used to show the relationship between static pressure and airflow at a given fan speed. The fan laws can also be used to predict the new operating point of a fan if the speed is changed. From the first fan law, it can be seen that the ratio of the fan speed is equal to the ratio of the fan speed. Given that at 1000 rpm the airflow is 24000 cfm from Figure 8-7, the first fan law would predict that the airflow for this fan operating at 1050 rpm would be as follows:

Figure 8-8 Family of Fan Curve Model



$$\frac{\text{cfm}_1}{\text{cfm}_2} = \frac{\text{rpm}_1}{\text{rpm}_2}$$

$$\frac{24000 \text{ cfm}}{\text{cfm}_2} = \frac{1000 \text{ rpm}}{1050 \text{ rpm}}$$

$$\text{cfm}_2 = (24000 \text{ cfm})\left(\frac{1050\text{rpm}}{1000\text{rpm}}\right)$$

$$\text{cfm}_2 = 25200 \text{ cfm}$$

Similarly, the second fan law would predict that the static pressure resulting from an increase in fan speed would increase as the square of the ratio of the change in fan speed. For a fan with the fan curve illustrated in Figure 8-7, the static pressure would be predicted to increase as follows:

$$\frac{\text{SP}_1}{\text{SP}_2} = \left(\frac{\text{rpm}_1}{\text{rpm}_2}\right)^2$$

$$\frac{2.5 \text{ in wg}}{\text{SP}_2} = \left(\frac{1000 \text{ rpm}}{1050 \text{ rpm}}\right)^2$$

$$\text{SP}_2 = (2.5 \text{ in wg})\left(\frac{1050\text{rpm}}{1000\text{rpm}}\right)^2$$

$$\text{SP}_2 = 2.8 \text{ in wg}$$

This increase in airflow through the fan does not come without a cost. The fan laws predict that increasing the speed of the fan to increase airflow and static pressure also increases the required power input or brake horsepower required to drive the fan. The cube of the ratio of the speed change is inversely related to the ratio of the change in fan brake horsepower as shown in the third fan law. The change in fan speed from 1000 rpm to 1050 rpm will result in the following increase in fan brake horsepower:

$$\frac{\text{Bhp}_1}{\text{Bhp}_2} = \left(\frac{\text{rpm}_1}{\text{rpm}_2}\right)^3$$

$$\frac{14.5 \text{ Bhp}}{\text{Bhp}_2} = \left(\frac{1000 \text{ rpm}}{1050 \text{ rpm}}\right)^3$$

$$\text{Bhp}_2 = (14.5 \text{ Bhp})\left(\frac{1050 \text{ rpm}}{1000 \text{ rpm}}\right)^3$$

$$\text{Bhp}_2 = 16.8 \text{ Bhp}$$

Therefore, increasing the fan speed from 1000 rpm to 1050 rpm will result an increase in power to drive the fan from 14.5 Bhp to 16.8 Bhp. This is a 16 percent increase in power to drive the fan in order to increase the airflow from 24000 cfm to 25200 cfm or 5 percent. Since power is energy per time, this increase in speed also results in an increase in energy required to run the fan for a given period of time by 16 percent. Therefore, this increase in fan speed may not only require a larger motor that will increase the initial installation cost but also will increase the operating cost over the life of the installation.

This change in operating point is illustrated in Figure 8-9. The original operating point for the fan at 1000 rpm was 24000 cfm at a static pressure of 2.5 in. wg. By increasing the fan speed to 1050 rpm, the airflow increased to 25200 cfm and the static pressure increased to 2.8 in. wg. In addition, the change in speed from 1000 rpm to 1050 rpm also resulted in an increase in required brake horsepower to drive the fan from 14.5 Bhp to 16.8 Bhp.

8.5 AIR HANDLING UNITS

An air-handling unit (AHU) is used to condition supply air to zones in central HVAC systems that include central cooling and heating equipment in a central plant. Air handling units are usually located throughout commercial and institutional buildings in fan or mechanical equipment rooms near the zones that they serve. A schematic diagram of a simple air-handling unit is shown in Figure 8-10. As can be seen from Figure 8-10, the air handling unit contains an air filter for cleaning outside air and return air, a cooling coil that is essentially a water-water-to-air heat exchanger for cooling incoming air, a heating coil which is also a water-to-air heat exchanger for warming incoming air, and a supply fan in a single enclosure. Chilled water and hot water are supplied by central cooling and heating equipment located in a central plant via chillers and boilers along with associated equipment such as pumps and cooling towers. A hydronic distribution system supplies the needed chilled and hot water to the air-handling unit cooling and heating coils.

Air-handling units can be supplied by the manufacturer as a pre-engineered packaged unit or custom built by the HVAC contractor and supplied to the field as a preassembled unit or field built from components at the project site. In addition to the basic air-handling unit components shown in Figure 8-10, air-handling units often include other components such as controls; motor starters and variable frequency drives (VFD); additional fans for outside and return air as well as multiple supply air fans for staging airflow; economizers and energy recovery equipment; various types of dampers; sound attenuators; air filtration and cleaning systems, humidification and dehumidification systems; among other options. The options selected for the air-handling unit will depend on the application. In addition, air-handling units can be built and supplied in a variety of configurations to meet space constraints in fan rooms and mechanical equipment rooms.

Figure 8-9 Fan Law Example Illustrated With Fan Curves

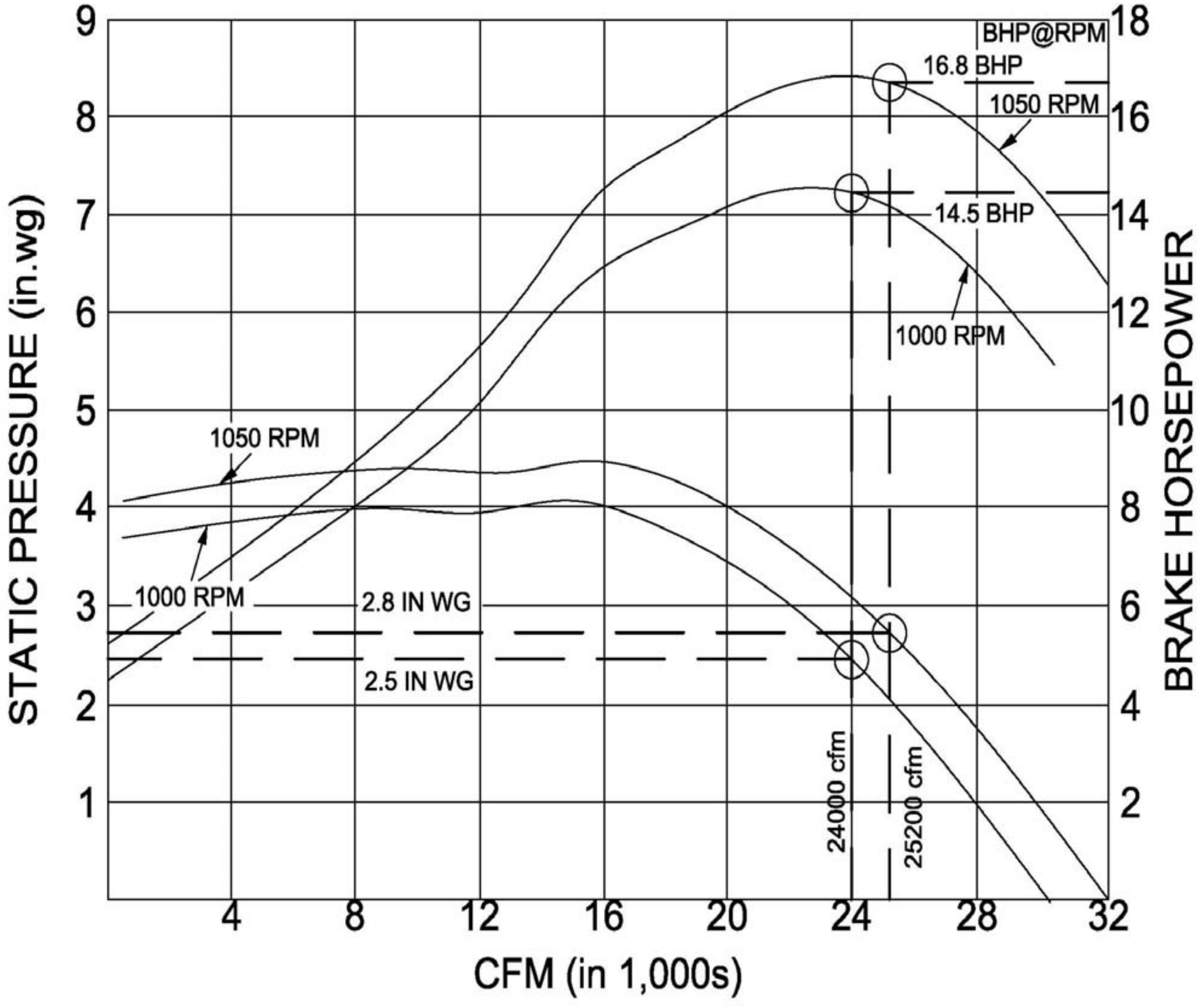
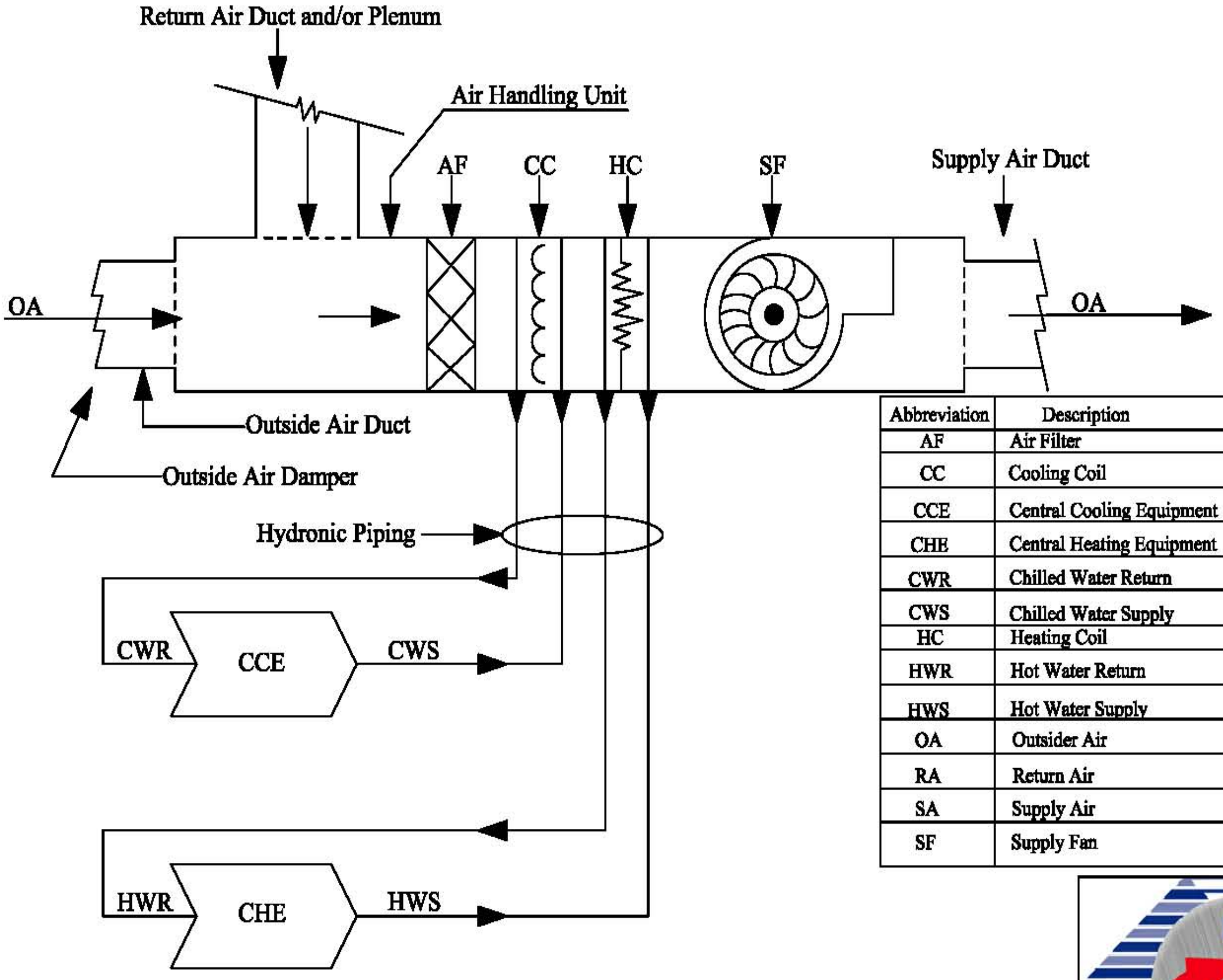


Figure 8-10 Air Handling Unit Schematic Diagram



Abbreviation	Description	Manual Reference
AF	Air Filter	Section 8.14
CC	Cooling Coil	------------
CCE	Central Cooling Equipment	Chapter VI
CHE	Central Heating Equipment	Chapter V
CWR	Chilled Water Return	Chapter VII
CWS	Chilled Water Supply	Chapter VII
HC	Heating Coil	------------
HWR	Hot Water Return	Chapter VII
HWS	Hot Water Supply	Chapter VII
OA	Outsider Air	------------
RA	Return Air	------------
SA	Supply Air	------------
SF	Supply Fan	Section 8.4

8.6 AIR DUCTS & PLENUMS

8.6.1 Air Duct Purpose

Air ducts serve the same purpose for air as the hydronic piping system covered in Chapter VII does for chilled and hot water. Essentially, air ducts provide a closed system for the supply and recovery of air throughout a building. Air ducts provide a means for moving the following types of air throughout a building:

- Supply Air
- Return Air
- Outside Air

Supply air is usually conditioned air supplied by the air-handling unit or the unitary HVAC equipment to the zone. Return air is the air extracted from the zone that is either returned to the air-handling unit or unitary HVAC equipment for reconditioning or exhausted to the outdoors. Outside air is the air brought in from the outdoors and supplied to zones for indoor air quality (IAQ) purposes. Usually, outside air is mixed with return air and reconditioned before being supplied to the space but in some instances outside air may be supplied directly to the space.

8.6.2 Air Duct Construction

Air ducts can either be rigid or flexible. Rigid air ducts are usually used for main and branch duct runs from the air handling unit or unitary HVAC equipment to the zone served. Flexible duct is normally used to connect between the main or branch duct and the air outlet or inlet that is located in the ceiling, wall, or floor of the zone served. The purpose of flexible duct is to provide flexibility when connecting to air outlets and inlets. The use of flexible duct is usually kept to a minimum because it tends to have increased pressure drop when compared to rigid duct.

Rigid duct in commercial and institutional buildings is usually made of sheet metal but it can be constructed from a variety of other materials. Metal ducts can be made of other than galvanized steel when the application, aesthetics, and atmosphere warrant it. Nonmetal ducts can also be constructed of fiberglass, plastic, concrete, and even cloth. Ducts can also be insulated to reduce thermal losses and sound transmission.

Rigid air ducts are normally rectangular but can also be square, round, oval, or any other geometric shape. Other geometric shapes are often used when there are space restrictions or aesthetic requirements when the duct is exposed. Flexible air duct is almost always round.

8.6.3 Air Duct Accessories

Duct accessories include a number of different units designed to improve the air distribution system performance such as silencers, turning vanes, and duct liners. In addition, air distribution systems also include various types of dampers including fire and smoke control dampers.

8.6.4 Additional Information On Air Ducts

SMACNA publishes a number of references and resources addressing the design, construction, and installation of air ducts. These publications include the following:

- *Fibrous Glass Duct Construction Standards*
- *Fire, Smoke And Radiation Damper Installation Guide For HVAC Systems*
- *HVAC Air Duct Leakage Test Manual*
- *HVAC Duct Construction Standards: Metal And Flexible*
- *HVAC Duct Systems Inspection Guide*
- *HVAC Systems Duct Design*
- *Residential Sheet Metal Guidelines*
- *Seismic Restraint Manual: Guidelines For Mechanical Systems*
- *Thermoset FRP Duct Construction Manual*
- *Thermoplastic Duct (PVC) Construction Manual*

The complete citations for these references and resources are provided in Appendix C of this manual.

8.6.5 Plenums

Air plenums are spaces within commercial and institutional buildings that are usually used to recover air from a conditioned zone for return to the air-handling unit or unitary HVAC equipment for reconditioning or exhaust to the outdoors. Plenums are used in lieu of installing return air ductwork between air inlets often referred to as return air grilles and return air ducts connected to air handling units or unitary HVAC equipment. Use of return air plenums reduce installation cost by eliminating ductwork as well as reduces congestion in building spaces used as plenums.

Plenums are part of the building structure and not part of the air duct system. Return air plenums are usually the space between the architectural ceiling and structural overhead in a building zone. Where a raised floor is used in high-tech office areas or data processing and communications rooms, the return air plenum is often the space between the raised floor and the structural floor.

8.7 VAV TERMINAL UNITS

8.7.1 VAV Terminal Unit Purpose

The purpose of a VAV terminal unit is to control the airflow of conditioned air that is delivered to a zone in response to that zone's thermal load. The ability of a VAV terminal unit to vary the volume of constant temperature air supplied to a space in response to the zone's changing thermal load allows the VAV system to maintain the desired temperature in the zone.

8.7.2 VAV Terminal Unit Operation

A basic VAV terminal unit is a device that is installed in ductwork downstream from the primary air supply and upstream from the air outlets that serve the zone as shown in Figure 8-11. This figure illustrates a VAV system with ducted return where the primary air supply is an air handling unit (AHU), a basic VAV terminal unit is inserted in the branch ductwork to control the amount of conditioned air supplied to the space, and three ceiling mounted diffusers are used to introduce the supply air into the space.

Figures 8-12 provides a diagram of the basic VAV terminal unit shown in Figure 8-11. As can be seen from Figures 8-12, a basic VAV terminal unit is a sheet-metal box with an air inlet and outlet and the following two operational components:

- Airflow Throttling Device
- Throttling Device Control Mechanism

The airflow throttling device is typically a rotating blade damper that is positioned by the control mechanism to allow the required volume of conditioned air to pass through the VAV terminal unit and into the zone served by the VAV terminal unit. The position of the damper in this basic VAV terminal unit can vary from fully closed where no air is supplied to the space to fully open which allows the maximum amount of supply air through the VAV terminal unit. The maximum amount of conditioned air that can pass through the VAV terminal unit is a function of not only the physical design and dimensions of the VAV terminal unit but also the primary air pressure at the inlet of the VAV terminal unit and the static pressure at the outlet of the VAV terminal unit.

The throttling device control mechanism in the basic VAV terminal unit that is shown in Figure 8-12 responds to a signal from one or more sensors in the zone. When thermal conditions or other variables being monitored deviate from the desired conditions, a signal is sent to the VAV terminal unit controller that adjusts the position of the VAV terminal unit damper so that the right amount of conditioned air can be supplied to the space. In Figure 8-11, the sensor is a thermostat located in the zone that monitors temperature. When the ambient temperature in the space deviates from the thermostat setting or setpoint, a signal is sent to the VAV terminal unit controller and the controller automatically adjusts the damper position to allow more or less conditioned air to be delivered to the space.

Figure 8-11 Basic Multi-Zone Cooling-Only VAV System

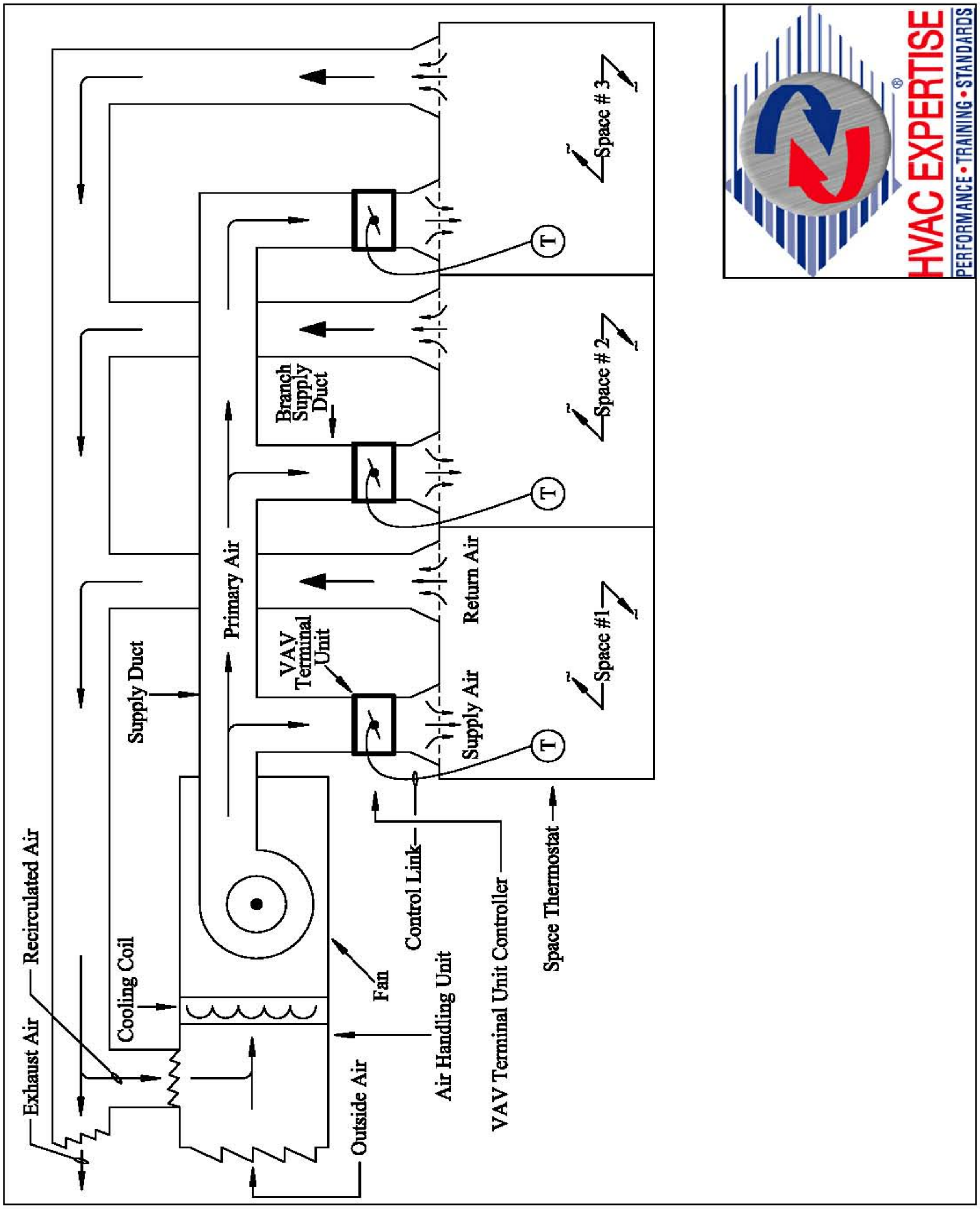
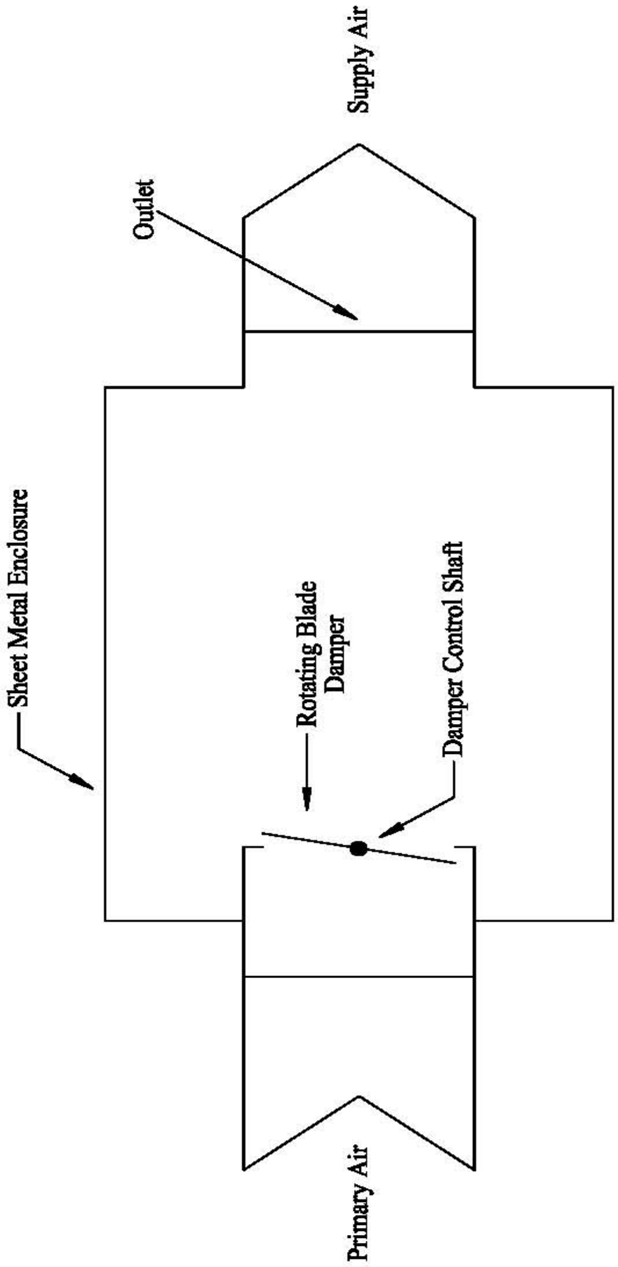


Figure 8-12 Basic VAV Single-Duct Terminal Unit: Functional Diagram



8.7.3 VAV Terminal Unit Inlet Pressure

The VAV terminal unit illustrated in Figure 8-12 is referred to as a pressure-independent VAV terminal unit because it is not capable of sensing and adjusting for changes in duct static pressure in order to regulate airflow into the zone. Up to this point, the affect of the supply duct static pressure on the airflow through a VAV terminal unit has not been considered. It has been assumed that the airflow through the VAV terminal unit is a function only of the position of its damper and that the static pressure in the supply duct serving the VAV terminal unit is constant. In reality, this is not the case.

VAV systems typically supply multiple zones and their associated VAV terminal units through a common supply duct using a common supply fan as shown in Figure 8-11. Each of the zones served by the supply system can have a changing thermal load that requires more or less conditioned air to be supplied to the zone in response to a signal from the zone’s thermostat. As a result, each VAV terminal unit damper is opening and closing in response to its zone’s thermal load which in turn impacts the static pressure in the supply duct. Even if the thermal load in Space #1 of Figure 8-11 remained unchanged and its VAV terminal unit damper remained in a fixed position, the opening and closing of VAV terminal unit dampers serving Spaces #2 and #3 would impact the supply duct static pressure and result in a changing airflow through the VAV terminal unit serving Space #1. The varying volume of air flowing into Space #1 as a result of changing supply duct static pressure will cause the temperature to unnecessarily fluctuate in the space and impact both occupant comfort and energy efficiency.

Pressure-Dependent VAV Terminal Units. The situation described above is what happens when a pressure-dependent VAV terminal unit is used. Pressure-dependent VAV terminal units were used when VAV systems were first introduced. Pressure-dependent VAV terminal units do not have the capability to measure and adjust their damper position in response to the supply duct static pressure in order to maintain the required airflow. The airflow supplied by a pressure-dependent VAV terminal unit to its zone depends on the static pressure in the supply duct and can vary depending on what is happening in other zones. For example, VAV terminal units that are close to the supply air fan are likely to supply too much air and VAV terminal units located further downstream from the supply air fan will probably supply too little air.

A pressure-dependent VAV terminal unit’s damper is controlled solely by the thermostat located in the zone that it serves. When the supply duct static pressure increases the damper remains in the same position and the airflow into the zone increases. This increase in cool air results in a gradual drop in space temperature until it is sensed by the thermostat and a signal is sent to the VAV terminal unit to close its damper. Similarly, when the static pressure drops in the supply air duct, the airflow through the VAV terminal unit also decreases and the temperature in the zone will increase if the thermal load remains constant. Again, when the temperature increase is sensed by the thermostat it will send a signal to the VAV terminal unit and it will open its damper allowing for greater airflow.

Pressure-dependent VAV terminal units respond to the changing supply duct static pressure through its impact on the temperature of the zone. Even though the thermostat continually monitors the temperature of the zone and adjusts the VAV terminal unit's damper accordingly, the response can be sluggish and result in unacceptable temperature variations within the space. As a result, VAV HVAC systems seldom use pressure dependent VAV terminal units that depend on a change in space temperature to adjust the VAV terminal unit's damper in response to a change in the supply duct static pressure. Instead, VAV HVAC systems utilize pressure independent VAV terminal units that measure the supply duct static pressure directly and adjust the VAV terminal unit's damper directly in response to changes in supply duct static pressure.

Pressure-Independent VAV Terminal Units. Nearly all VAV terminal units that are installed in new VAV HVAC systems or retrofitted into existing VAV HVAC systems are pressure independent. Pressure independent control of airflow through VAV terminal units requires accurate measurement of the pressure differential between the inlet and outlet of the terminal unit. This measurement is usually accomplished using an integral airflow-measuring device such as a multipoint airflow sensor located at the inlet of the VAV terminal unit as shown in Figure 8-13.

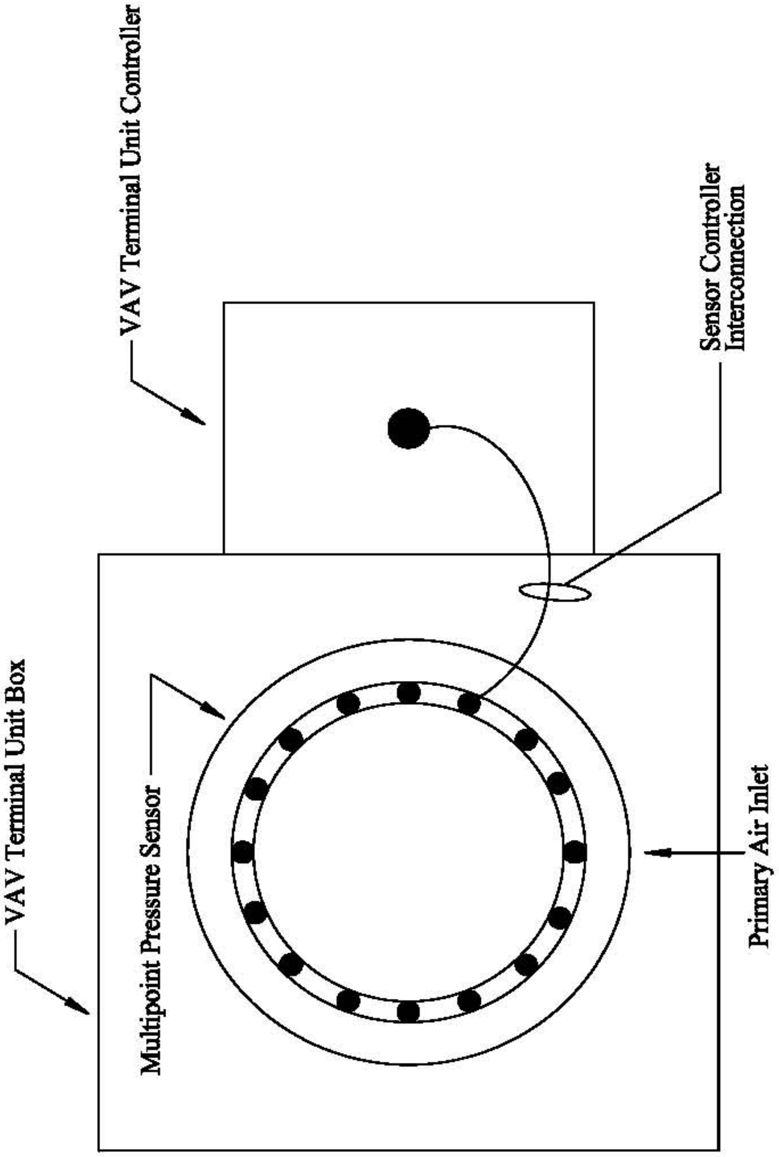
The output of the flow sensor at the VAV terminal unit inlet is fed into the terminal unit controller and used in conjunction with the signal from the zone thermostat to modulate the terminal unit damper in order to provide constant airflow through the terminal unit. As a result, the airflow through the VAV terminal unit is directly controlled and is independent of the supply duct static pressure at its inlet. Pressure independent VAV terminal units result in a more stable airflow through the VAV air terminal unit as well as result in minimum and maximum airflow settings that correspond to actual airflows rather than just the physical position of the VAV air terminal unit damper.

8.8 AIR OUTLETS & INLETS

8.8.1 Air Outlet & Inlet Function

Air outlets and inlets are the interface point between the HVAC air distribution system and the zone that they serve. Air outlets represent the point at which conditioned air is introduced into the space from the air distribution system and air inlets are the point at which the mixed air is extracted from the space and either returned to the HVAC system for reconditioning or exhausted to the outside. In commercial and institutional buildings, air outlets and inlets are normally installed in the ceiling because that is where the supply ductwork is typically installed and where either the return ductwork or plenum is located. However, air inlets and outlets can also be installed in walls and floors depending on the location of the supply and return air distribution system and the required zone air distribution patterns.

Figure 8-13 VAV Terminal Unit Inlet Multipoint Pressure Sensor



8.8.2 Air Outlet & Inlet Types

Air outlets and inlets are typically categorized as one of the follow types:

- Diffusers
- Grilles
- Registers

Diffusers. A diffuser is an air distribution system outlet. The purpose of a diffuser is to direct supply air in various directions and planes within a zone to promote the mixing of the conditioned supply air with the existing air. A diffuser is comprised of deflecting members used to direct the supply airflow into the zone. Diffusers are typically mounted in the ceiling and can be circular, square, or rectangular

Grilles. A grille is simply a louvered or perforated covering for an air passage opening that can be installed in the ceiling, wall or floor.

Registers. A register is a grille that is equipped with an internal damper that is usually manually operated to control the airflow through the register.

8.8.3 Air Outlet & Inlet Selection & Installation

The type, size, and location of air outlets and inlets in a zone are very important. Air outlets and inlets need to be sized so that they can supply the required airflow without causing an excessive pressure loss. An excessive pressure loss through the air outlet or inlet will require increased fan power to overcome it and increased noise due to the required higher air velocity through it. Air outlets and inlets must be located to allow the necessary mixing of conditioned supply air in the zone before it is extracted and to avoid air stratification in the zone.

Air outlets and inlets as well as their location in the zone are very important to occupant thermal and acoustic comfort as well as the perceived quality of the HVAC system. Unlike the rest of the HVAC system that is hidden from building occupants' sight, HVAC air outlets and inlets can be seen and heard by building occupants. The installation wrong air outlets and inlets or the installation of the right air outlets and inlets in the wrong location can result in an otherwise outstanding HVAC system being judged as inadequate or poor by building occupants. In addition, poor placement of air outlets and inlets can also result in unnecessary complaints and call backs after installation.

8.9 AIR DISTRIBUTION SYSTEM OPERATION

For a given airflow, the air distribution system produces a resistance to that airflow. As noted above, this resistance to airflow is referred to as static pressure. The system static pressure that the fan sees at its outlet is the sum of all the static pressure losses that occur as the air flows through the air distribution system. Resistance producing elements include ductwork, dampers, grills, coils, and anything else the air must pass through.

As airflow through the air distribution system changes, so does static pressure. The relationship between static pressure and airflow is given by the following equation:

$$\mathrm{SP} = \mathrm{K} \bullet \left(\mathrm{cfm}\right)^2$$

Where: SP = Static Pressure
K = Constant That Determines The Steepness Of The Curve
cfm = Airflow

An air distribution system curve that is based on the above equation is shown in Figure 8-14. As can be seen from the equation and Figure 8-14, the air distribution system static pressure is directly proportional to the square of the airflow. Therefore, doubling the airflow through the distribution system will result in the static pressure increasing by four times.

The above equation relates static pressure and airflow for a given air distribution system under specified conditions. Any physical change in the air distribution system will result in a shift to a new system resistance curve. Specifically, a change in the air distribution system will result in a new constant “K” in the above equation. If a change increases the air distribution system resistance then the constant K will increase resulting in a new and steeper system resistance curve as illustrated by System Curve #2 in Figure 8-15. Similarly, if the air distribution system resistance decreases then the constant “K” will also decrease resulting in a new system resistance curve that is not as steep as the original System Curve #1.

To illustrate how a system distribution curve can change in an actual HVAC system, consider a VAV system. If the dampers in downstream VAV air terminals close to reduce airflow to a zone, additional resistance is introduced in the air distribution system and the system resistance curve will shift from the original System Curve #1 to the steeper System Curve #2 in Figure 8-15. The same shift to a new system curve can occur when system filters become dirty or when anything else occurs that increases the air distribution system’s resistance to airflow. Similarly, if the dampers in downstream VAV air terminals open to increase airflow to a zone then resistance to airflow will decrease and the system resistance curve will which will shift from the original System Curve #1 to the new flatter system curve.

Figure 8-14 System Curve

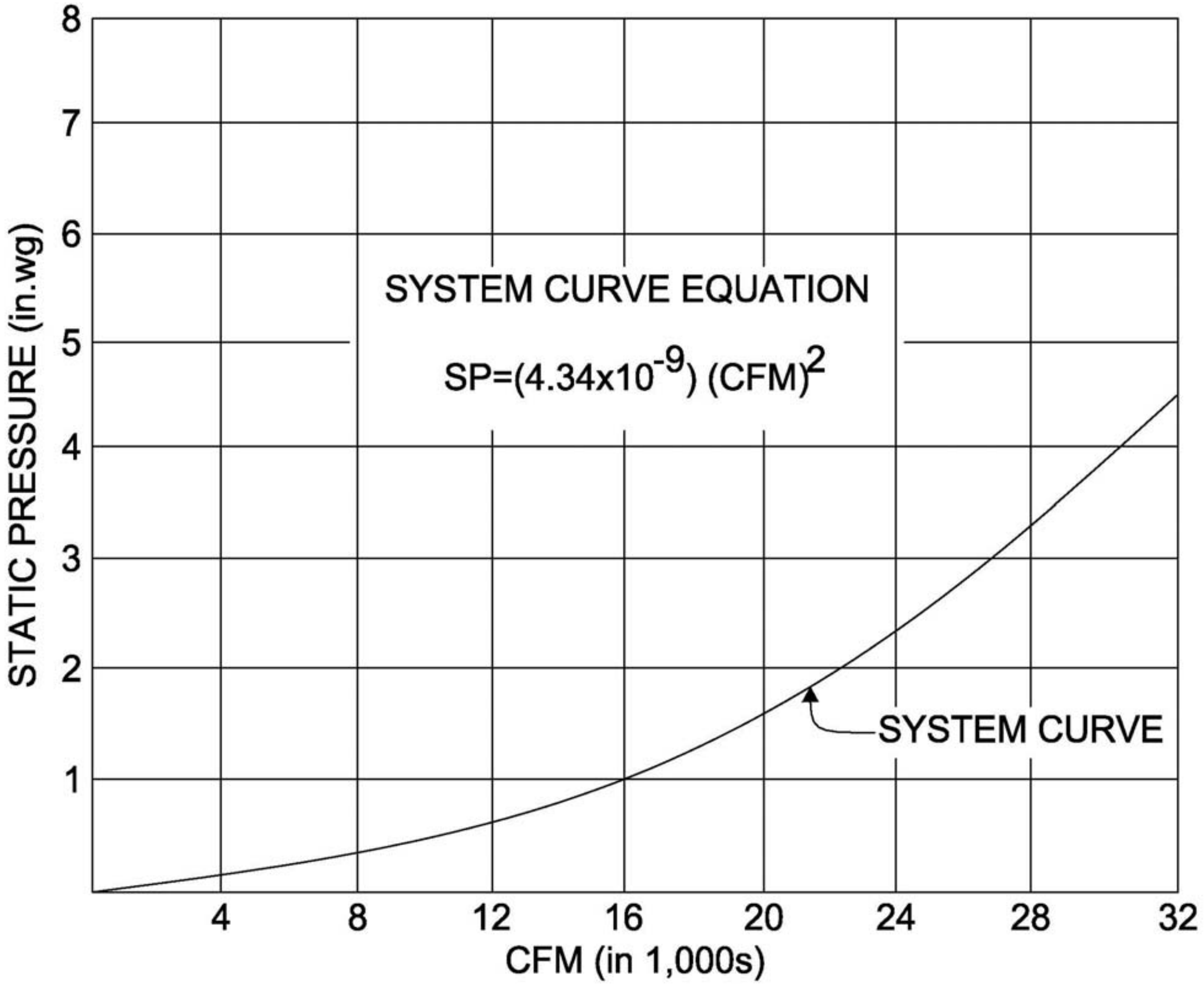
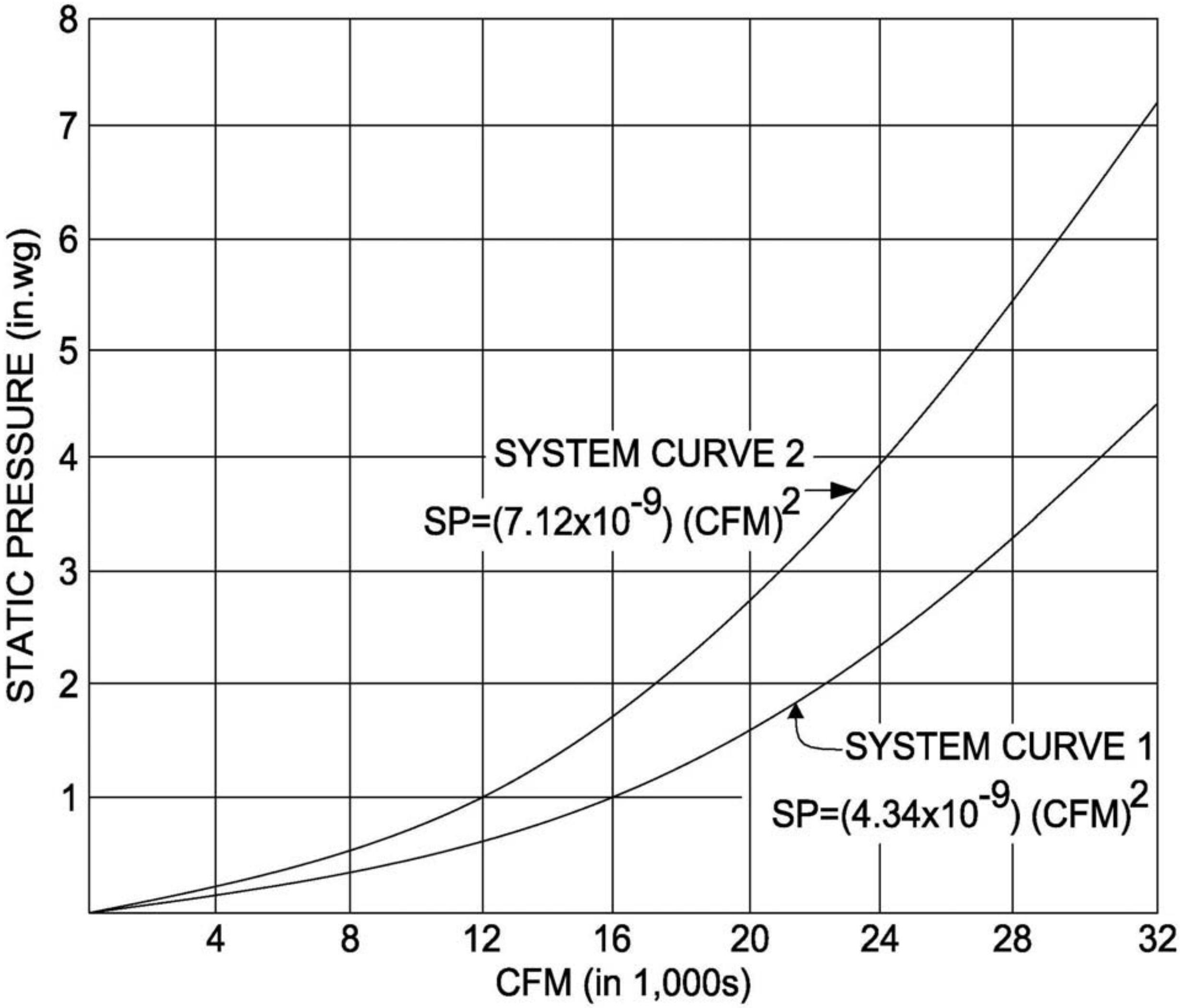


Figure 8-15
System Curve Change Due To Increased Resistance To Flow



8.10 AIR DISTRIBUTION SYSTEM OPERATING POINT

The previous two sections introduced fan and system curves. As discussed in Section 8.4.5, a fan curve describes the operating characteristics of a particular fan and consists of a series of airflow and static pressure points that a fan can operate at for a given fan speed. Similarly, the system resistance curve was defined in Section 8.9 as a series of airflow and static pressure points that the air distribution system will operate at. By superimposing the system resistance curve shown in Figure 8-14 on the fan performance curve provided in Figure 8-7, the air distribution system operating point can be determined. As can be seen from Figure 8-16, the air distribution system operating point occurs at the intersection of the system resistance curve and the fan performance curve. Under the conditions specified, the air distribution system is delivering 24,000 cfm at a static pressure of 2.5 in. wg with the fan operating at 1000 rpm.

8.11 AIR DISTRIBUTION SYSTEM DYNAMICS

Opening or closing a damper in a supply duct will result in more or less air being supplied to the zone that the air distribution system is serving. As discussed in Section III, a VAV-CAT HVAC system supplies variable amounts of constant temperature air to a space in order to maintain the desired temperature in the space. The amount of constant temperature air supplied to the space is determined by the damper settings in the VAV terminal units serving the zone.

If the thermal load in the zone never changed, a manual damper could be installed and this damper could be adjusted once during building commissioning and never changed. This would result in a constant system operating point as shown in Figure 8-16. Unfortunately, this is not the case and the thermal load in any HVAC zone is always changing due season, time of day, daily weather patterns, number of people in the zone, occupant activity, equipment use, and other variables. Therefore, to maintain the desired temperature in the zone the amount of constant-temperature air delivered to the zone must varied in response to changes in zone thermal load. This is accomplished automatically by sending a signal from the zone thermostat that directs the VAV terminal units to open to cool the space or close to allow the space to warm.

Changes in the VAV terminal unit damper settings not only change the amount of air delivered to the zone but also change the air distribution system resistance curve as discussed in Section 8.9 and illustrated in Figure 8-15. By overlaying the system operating curves shown in Figure 8-15 on the fan-operating curve provided in Figure 8-7, the impact of a changing system-operating curve on air distribution system operation is illustrated in Figure 8-17.

As can be seen from Figure 8-17, as the VAV terminal unit dampers close the air distribution system offers more resistance to airflow and the system resistance curve shifts from System Curve #1 to System Curve #2 with a corresponding shift in fan operating point along the fan operating curve. This shift results in the desired reduction in airflow but also results in an increase in static pressure. Because this method of adjusting airflow in response to changing zone thermal conditions results from the system traversing from System Operating Point #1 to System Operating Point #2 it is referred to as "riding the fan curve."

Figure 8-16 System Operating Point

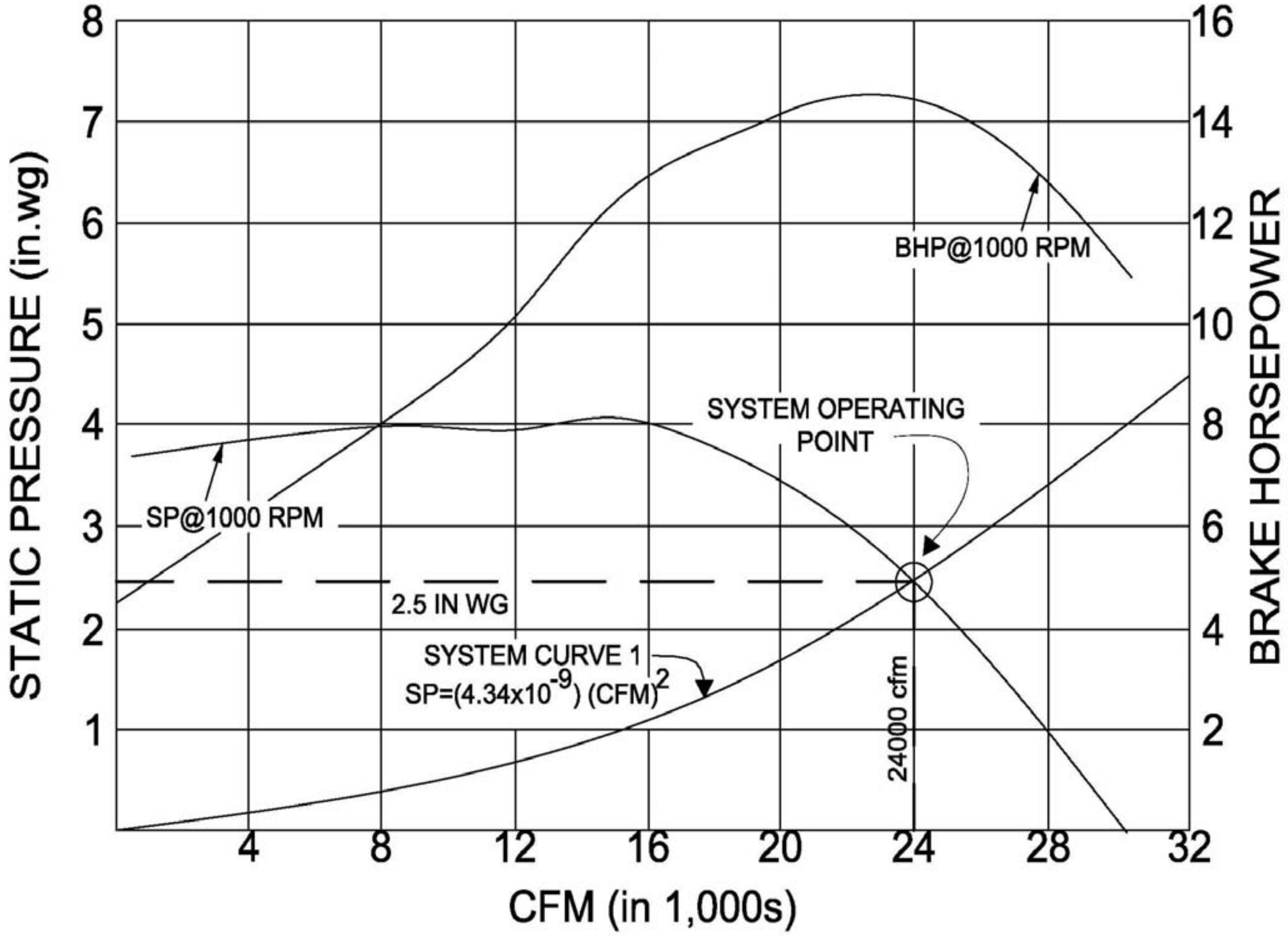
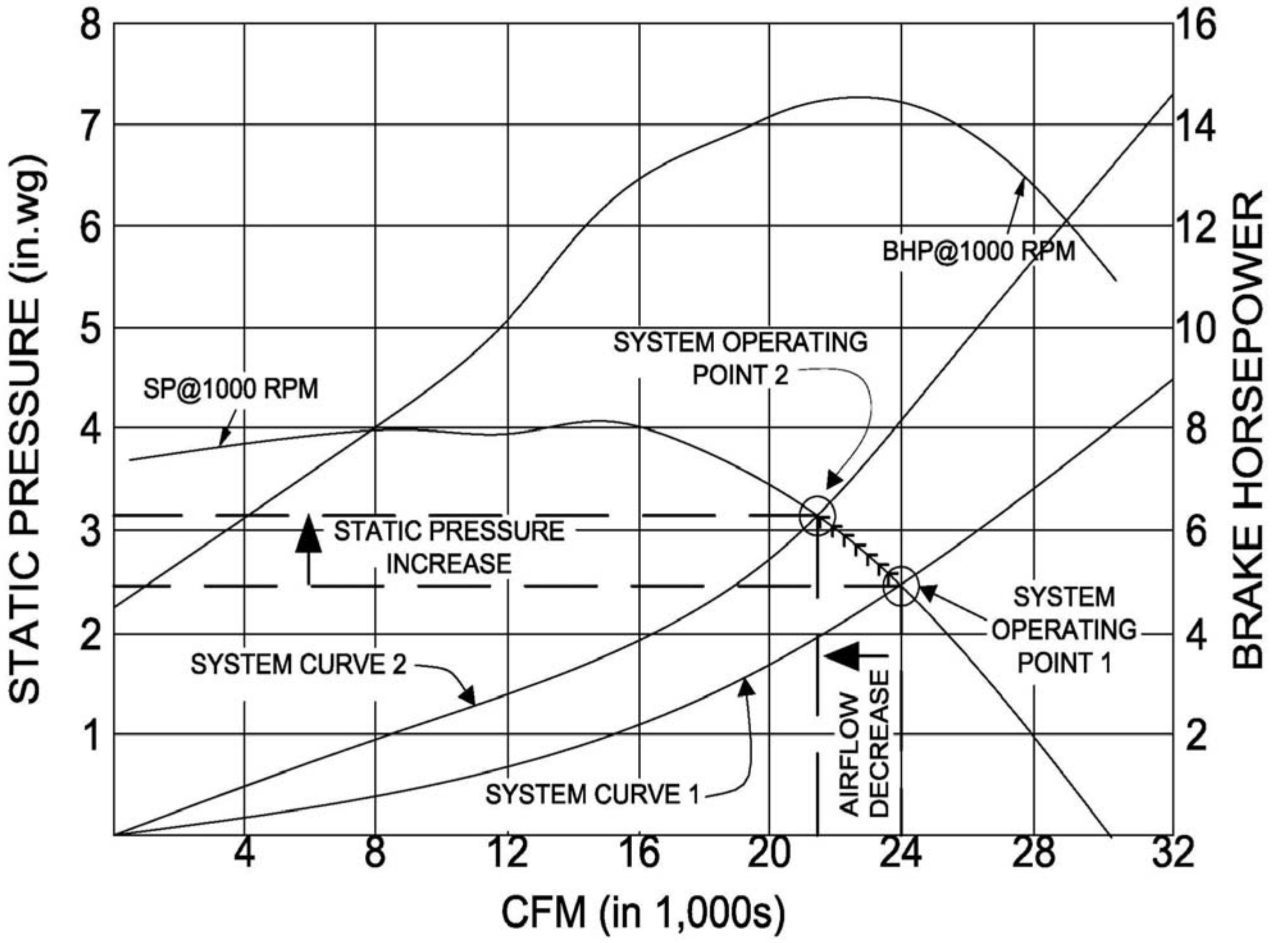


Figure 8-17 Fan Airflow Modulation "Riding the Fan Curve"



Adjusting supply fan airflow by “riding the fan curve” can be used with any centrifugal fan but it is most efficient when a forward-curved centrifugal fan is used. However, “riding the fan curve” can result in problems if the airflow is required to vary more that just a little during operation. Problems that can result from “riding the fan curve” over a wide range of airflows can include the following:

- Excessive duct pressure.
- Excessive duct leakage.
- Excessive noise at VAV terminal units.
- Erratic VAV terminal unit performance.
- Fan surge causing air pulsation in duct system.
- Negligible energy savings.

8.12 SYSTEM OPERATING POINT & FAN SPEED

Figure 8-18 superimposes the system operating curves shown in Figure 8-15 on fan curve for 1000 rpm shown in Figure 8-7 along with the fan curve for the same fan operating at 900 rpm. Instead of riding the fan curve from System Operating Point #1 to System Operating Point #2 as discussed in the previous section, the reduced system airflow could also be achieved by reducing the fan speed. As shown in Figure 8-18, reducing the fan speed from 1000 rpm to 900 rpm results in a shift from System Operating Point #1 to System Operating Point #3 along the system operating curve. At System Operating Point #3, the airflow is now the desired 21200 cfm and the static pressure is 2.0 in wg. Unlike riding the fan curve to achieve reduced system airflow, reducing fan speed results in not only reduced airflow but also reduced static pressure which eliminates most of the problems with riding the fan curve. In addition, reducing the fan speed from 1000 rpm to 900 rpm reduced the power required by the fan from 14.5 Bhp down to 10.5 Bhp or about 28 percent.

The reduction in fan power can also be approximated using the third fan law:

$$\frac{\text{Bhp}_1}{\text{Bhp}_2} = \left(\frac{\text{rpm}_1}{\text{rpm}_2}\right)^3$$

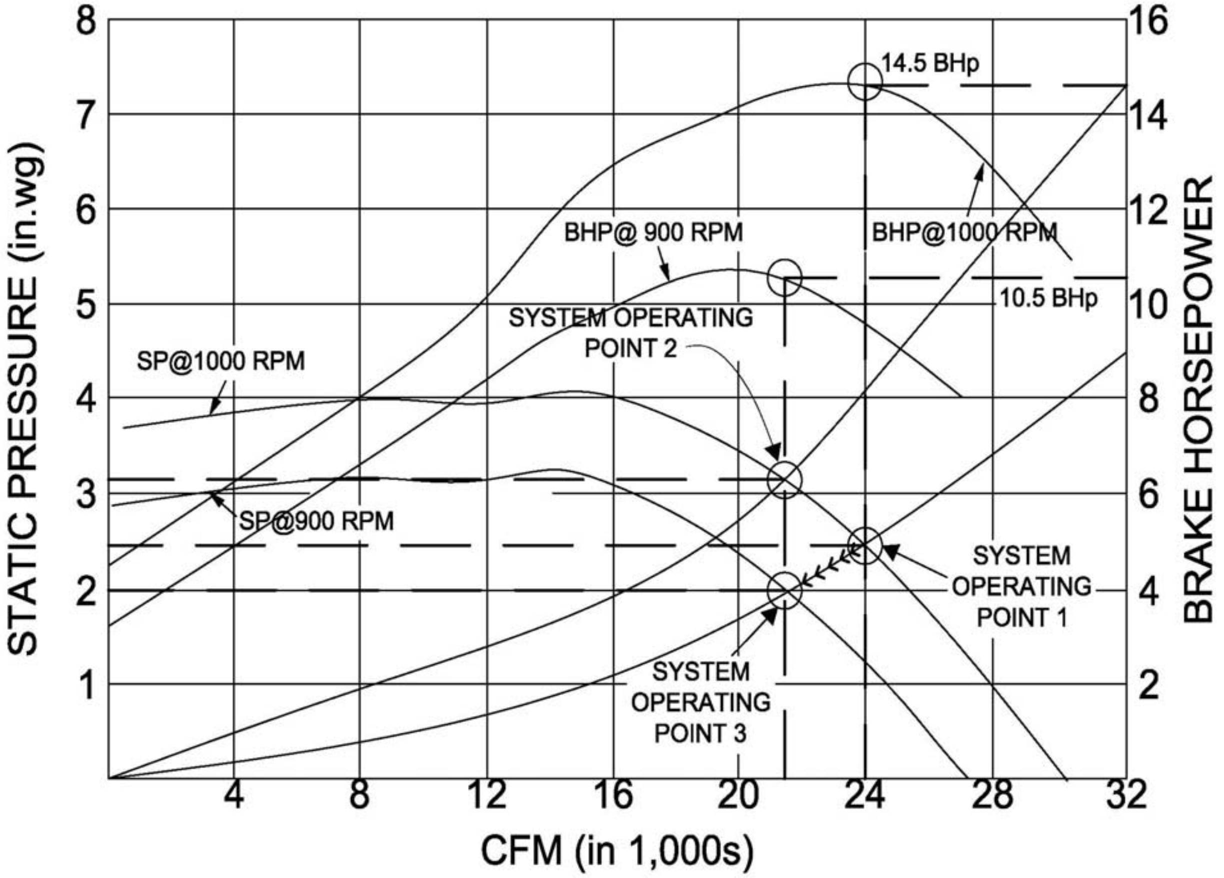
$$\frac{14.5\ \text{Bhp}}{\text{Bhp}_2} = \left(\frac{1000\ \text{rpm}}{900\ \text{rpm}}\right)^3$$

$$\text{Bhp}_2 = (14.5\ \text{Bhp})\left(\frac{900\ \text{rpm}}{1000\ \text{rpm}}\right)^3$$

$$\text{Bhp}_2 = 10.6\ \text{Bhp}$$

Using variable frequency drives (VFDs) to modulate supply fan airflow by adjusting fan speed will reduce problems caused by riding the fan curve and result in significant energy savings.

Figure 8-18 Varying Fan Operating Points With Fan Speed



8.13 VARIABLE FREQUENCY DRIVES

8.13.1 What Is A Variable Frequency Drive?

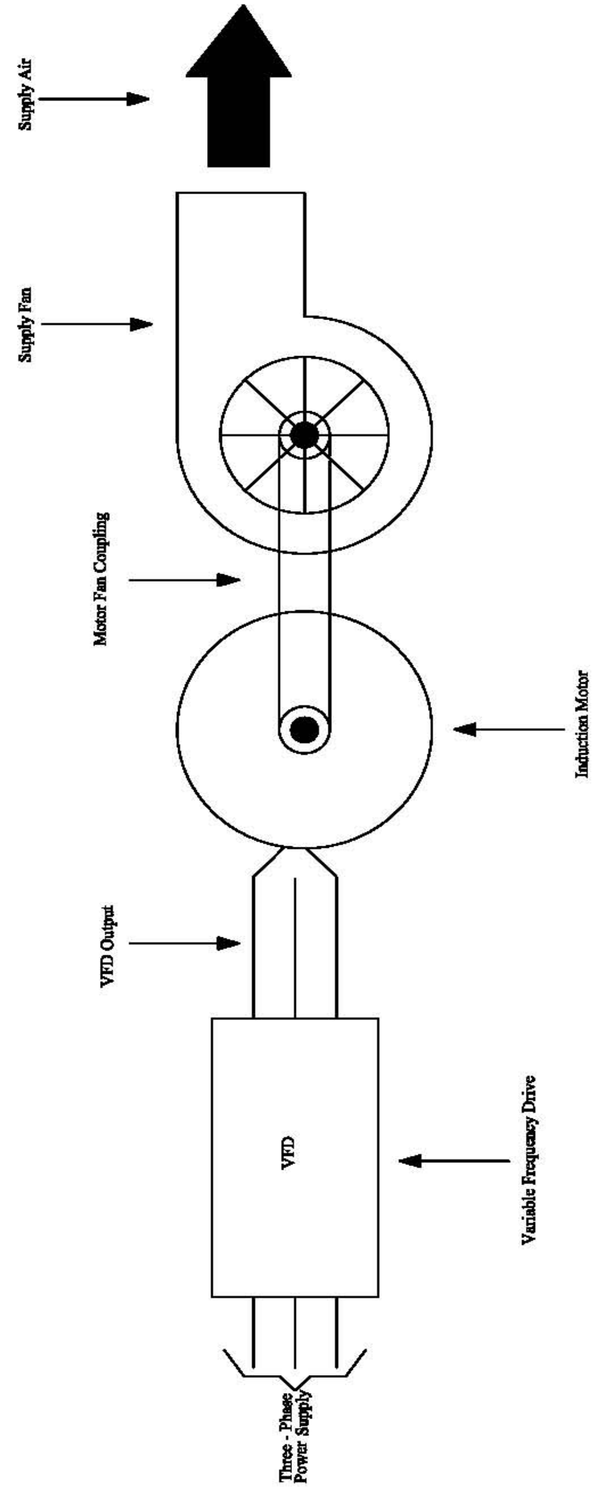
Varying fan airflow can be accomplished using variable frequency drives or VFDs. VFDs work with alternating-current (AC) induction motors whose shaft speed is a function of the frequency of the applied AC voltage and the motor's construction. VFDs electronically convert the applied 60 Hertz (Hz) or cycles per second voltage supplied by the building power distribution system to a higher or lower frequency waveform which is used to power the induction motor and results in a corresponding change in motor shaft speed. The motor's shaft is coupled to the supply fan and results in a corresponding change in fan speed and operating characteristics. Figure 8-19 provides a functional diagram of a VFD drive system. VFDs provide better system control, are more efficient, and more economical on a life cycle cost basis than other methods of supply fan airflow control including riding the fan curve. VFDs are used extensively in commercial and institutional VAV HVAC systems today.

8.13.2 VFD Operation

A VFD is a solid-state electronic power conversion device that converts a sinusoidal input voltage of constant frequency and magnitude into a variable frequency and magnitude voltage at its output. The VFD controls the speed and torque characteristics of the squirrel-cage induction motor that is used to drive the supply fan. The purpose of a VFD is to drive the fan at the speed required to deliver the necessary airflow to the zones that it supplies as well as optimize the operation of the motor. A VFD controls the speed, torque, direction, and resulting horsepower output of the induction motor that it serves.

In the United States, the frequency of the VFD input voltage is 60 Hz and the nominal three-phase voltages typically available in commercial and institutional facilities are 208, 240, and 480 volts. A VFD is a multistage device that takes its three-phase input voltage and converts it to DC by rectifying and filtering it in the first stage. The second stage of a VFD is referred to as an inverter because it takes the DC output from the first stage and converts it to a variable frequency and magnitude output voltage. Depending on the design of the VFD, the output voltage might be a quasi sinusoidal voltage waveform consisting of fixed duration pulses of varying polarities and magnitudes or it might be a series of constant magnitude voltage pulses with varying polarity and width referred to as pulse-width modulation (PWM).

Figure 8-19 VFD Drive System Functional Diagram



8.13.3 Impact Of Fan Speed Control

As shown in Figure 8-11, each space is served by a dedicated VAV terminal unit which in turn is controlled by the thermostat in that space. In each case, the thermostat in the zone controls the VAV terminal unit's damper position and sets it to provide the required airflow for the space cooling load. The supply fan serving the spaces in Figure 8-11 is a forward-curved centrifugal fan whose fan performance curve is provided in Figure 8-18. Also plotted on Figure 8-18 is the system curve that relates the static pressure drop to the airflow for the air distribution system. As discussed previously, the intersection of the constant speed fan curve and the system resistance curve yields the system operating point which is System Operating Point #1.

Under normal operating conditions, the VAV terminal units will seldom all require full cooling at one time and therefore the system will normally operate at a reduced airflow. Further, cooling loads will fluctuate throughout the day in each space depending on a number of factors and when cooling loads are dropping in the spaces the VAV terminal unit dampers close further resulting in reduced airflow and increased static pressure in the supply duct. Figure 8-18 illustrates how the system operating point moves along the constant-speed fan performance curve as the duct static pressure increases. As a result of the increasing static pressure in the supply duct the system operating point moves up the fan performance curve from its original operating point at System Operating Point #1 to its new operating point at System Operating Point #3. As discussed previously, this method of adjusting supply fan airflow in response to changes in the system demand is referred to as "riding the fan curve." As can be seen from Figure 8-18, this reduced airflow results in an increase in static pressure and no significant change in required fan power.

Using a VFD on a supply fan results in a new fan curve at 900 rpm as shown in Figure 8-18. Instead of moving up the fan curve to System Operating Point #2, the fan speed can be reduced using a VFD to match the reduced system airflow requirement while simultaneously reducing the static pressure in the supply duct. From Figure 8-18 it can be seen that reducing fan speed results in a shift from the original System Operating Point #1 to the new System Operating Point #3 along the original system operating curve. With static pressure decreasing along with airflow, the operational concerns associated with increased static pressure from "riding the fan curve" are eliminated using a VFD. In addition fan power is reduced by 28 percent along with a corresponding reduction in energy use.

8.14 AIR CLEANING DEVICES

8.14.1 Need For Air Cleaning Devices

Indoor air pollutants are unwanted and sometimes dangerous to building occupants. The best way to eliminate the risk of indoor air pollutants is to control the use of chemicals and other contaminants that could become indoor pollutants and ventilate the building using outside air. Unfortunately, total building ventilation with outside air may be limited due to economics, HVAC system capabilities during weather extremes, and the fact that there may be objectionable levels of contaminants in the outside air. Air cleaning devices are intended to reduce the need for outside air by physically removing pollutants from both HVAC return air and outside air before supplying the conditioned air to the zone. Air cleaning devices should be used in conjunction with source control and ventilation but not as a substitute. Air cleaning devices have limitations and these limitations need to considered and accounted for.

8.14.2 Categories Of Air Pollutants

Indoor air pollutants can be classified as either:

- Particulate
- Gaseous

Particulate pollutants include inanimate particulates like dust, smoke, and pollen as well as living particulates such as dust mites, molds, bacteria, and viruses. Gaseous pollutants are either by products of combustion or chemicals being used in the building or off gassed from building furnishings and materials. Gaseous pollutants that result from combustion includes gas cooking and vehicle exhaust. Gaseous pollutants from building materials include adhesives, paints, cleaning products, and pesticides among many others.

8.14.3 Particulate Air Filtration

Two types of air cleaning devices that physically remove particulate pollutants from the air are:

- Mechanical Air Filters
- Electronic Air Cleaners

Mechanical Air Filters. Mechanical air filters remove particles by capturing them on filter materials. Mechanical air filters can capture and remove dust, pollen, dust mites, and some molds. Mechanical filters are rated in accordance with the efficiency by which they remove particulate pollutants from the air stream that passes through it. The efficiency of a mechanical air filter is determined by the filter's minimum efficiency reporting value (MERV).

Flat or panel air filters with a MERV of 1 to 4 are usually used in residential furnaces and air conditioners. Medium efficiency filters with a MERV of 5 to 13 are reasonably efficient at removing both small and large particulate pollutants.

Pleated or extended surface filters are typically used in commercial and institutional air distribution systems. Medium efficiency filters that have a MERV of between 7 and 13 are generally less expensive than high efficiency particulate air (HEPA) filters but can be nearly as efficient at removing particulate pollutants while reducing the expected pressure across a HEPA filter. Using a filter with a MERV rating between 7 and 13 in lieu of a HEPA filter should result in increased airflow and a resulting reduction in fan power and noise.

Higher efficiency filters with a MERV of 14 to 16 are similar in appearance to HEPA filters but are not. HEPA filters have a MERV value of from 17 to 20.

Electronic Air Cleaners. Electronic air cleaners use electrostatic attraction to trap and remove particulate pollutants from the air stream. The air flows through an ionization section of the electronic air cleaner where the pollutant particles receive an electrostatic charge. The charged pollutant particles are then attracted to and accumulate on a series of flat plates referred to collectively as the collector that carry an opposite charge. Electronic air cleaners that operate as described in this section are sometimes referred to as electrostatic precipitators.

Unlike mechanical air filters, there is no standard for measuring the effectiveness of an electronic air cleaner. Electronic air cleaners are very good at removing small size particles from the air stream but not as efficient at removing larger particulates. Electronic air cleaners can also produce ozone which is a lung irritant.

8.14.4 Gas-Phase Air Filtration

Gas-phase air filtration removes gaseous pollutants from the air stream by using a material referred to as a sorbent. A commonly used sorbent is activated carbon or charcoal that absorbs the gaseous pollutants as they pass through the gas-phase air filter. Sorbents used in gas-phase air filtration will only absorb certain pollutants and will not reduce the concentrations of pollutants that they are not designed to absorb. When considering the use of gas-phase air filtration, always be sure that the sorbent selected will absorb the anticipated contaminant and reduce the concentration to an acceptable level.

8.14.5 Pollutant Destruction

In the case of living particulates it is often desired to destroy the particulate rather than just capturing it and retaining it in a filter which can also be dangerous. The most common method for destroying living particulates used in commercial and institutional buildings is ultraviolet germicidal irradiation (UVGI) which uses ultraviolet light. UVGI systems are available that will destroy many biological pollutants including viruses, bacteria, allergens, and molds that are airborne or found on HVAC cooling coils, drain pans, and ductwork. UVGI is not a substitute for mechanical air filters and should UVGI should be used in conjunction with mechanical filters when required.

CHAPTER IX
CENTRAL HVAC SYSTEMS

9.1 INTRODUCTION

As discussed in Chapter III, the purpose of an HVAC system is to provide a suitable environment that meets the needs of the occupants, the activity that takes place in the building, or both. Most central HVAC system in large commercial and institutional buildings are air-hydronic systems with zone cooling being accomplished by introducing cool air into the space using an air distribution system and zone heating being achieved by either the air supplied to the space or using convection terminal units with hot water. HVAC systems for smaller commercial and institutional buildings are typically all-air central HVAC systems using unitary HVAC equipment as discussed in Chapter 4.

This chapter will focus on central HVAC systems for large commercial buildings where cooling and heating is provided by central heating and cooling equipment that use hot and chilled water as the primary heat transport media and provide conditioned air to zones using local air handling units and an air distribution system. The two basic central HVAC systems that were first introduced in Chapter III and will be covered in this chapter are as follows:

- Constant Air Volume – Variable Air Temperature (CAV-VAT)
- Variable Air Volume – Constant Air Temperature (VAV-CAT)

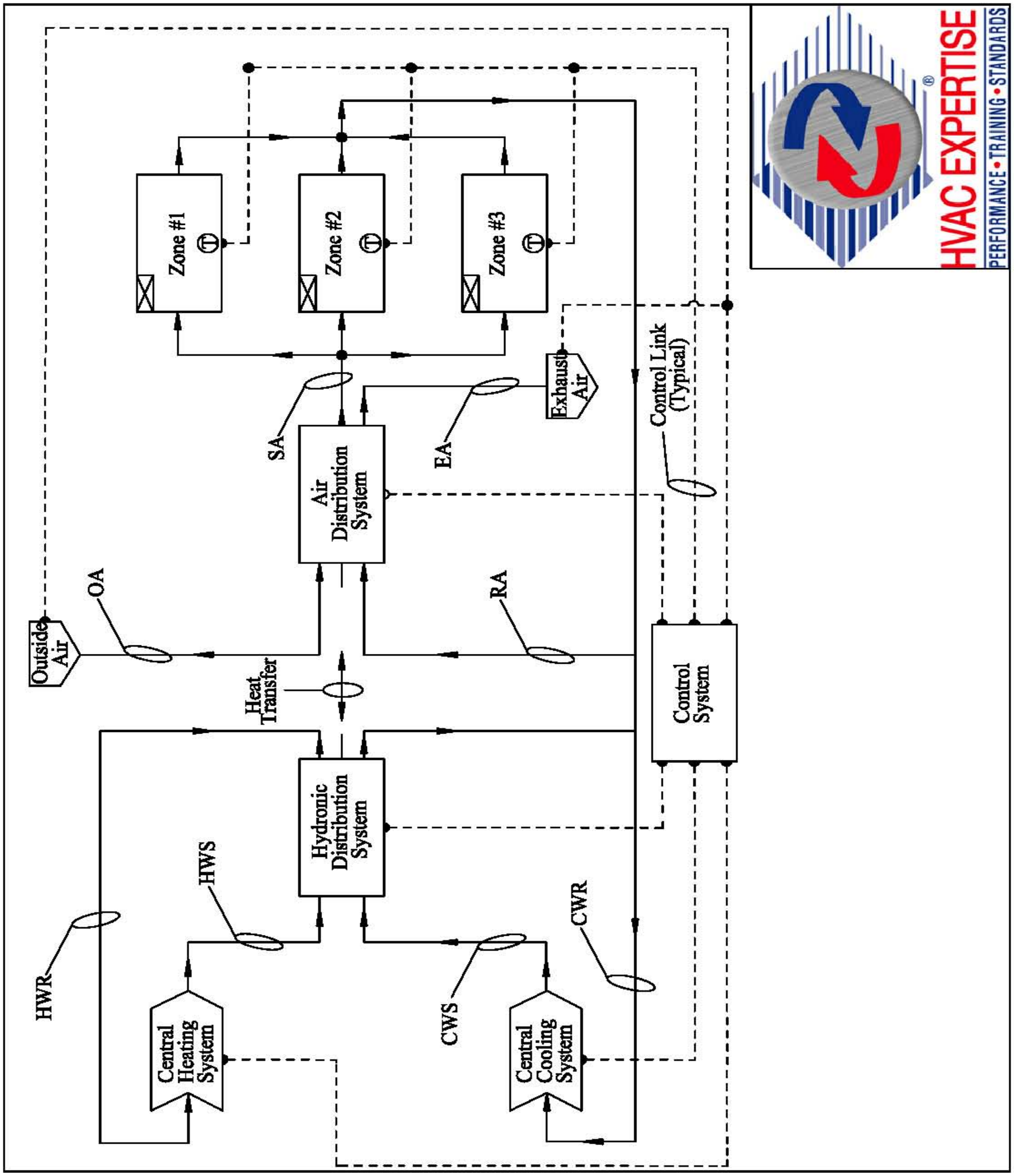
VAV-CAT HVAC systems are usually simply referred to as “VAV systems” and will be covered first because VAV systems are the most common type of HVAC system being installed in large commercial and institutional buildings today. VAV systems are generally more energy efficient, provide greater occupant comfort, and are more easily modified or reconfigured to meet changing building needs than CAV-VAT HVAC systems. CAV-VAT HVAC systems are usually referred to as “constant-volume systems.” These systems are still being used in many existing buildings and are also used in new buildings or parts of buildings where a constant volume air supply is required due to the type of activity taking place in the building or space. Therefore, constant-volume HVAC systems are also discussed in this chapter along with a comparison between these two HVAC system types.

9.2 CENTRAL HVAC SYSTEM SUBSYSTEMS

9.2.1 Five Primary Central HVAC Subsystems

A central HVAC system is one where the heating source, cooling source, or both are centrally located and serve a significant part of the building’s HVAC load. Central HVAC systems for commercial and institutional buildings are comprised of five primary subsystems. These five subsystems and their interrelationships are illustrated in the simplified block diagram of a central HVAC system in Figure 9-1. The five primary subsystems that make up a central HVAC system are as follows:

Figure 9-1 Central HVAC System Simplified Block Diagram



CENTRAL HVAC SUBSYSTEM	MANUAL CHAPTER
Central Heating Subsystem	V
Central Cooling Subsystem	VI
Hydronic Distribution Subsystem	VII
Air Distribution Subsystem	VIII
Control Subsystem	X

Each of these subsystems are covered in the chapter indicated in the table and will be briefly discussed in the following paragraphs.

9.2.2 Central Heating Subsystem

The central heating subsystem operation and components are covered in Chapter V of this manual. As can be seen in Figure 9-1, the central heating system consisting of boilers and pumps that provide hot water to the hydronic distribution system to be distributed throughout the building to either heat the air that is supplied to the zones through the air distribution system, through convection terminal units located in the zones, or both. The cooler hot water is then returned through the hot water return piping to the central heating system for reheating and recirculation.

9.2.3 Central Cooling Subsystem

Chapter VI covers the central cooling subsystem that typically consists of chillers, pumps, and a cooling tower. The central cooling system supplies chiller water to air handling units through the hydronic distribution system. The air-handling units use the chilled water to condition the air supplied to the zones by cooling it and sometimes dehumidify it also. The warmed chilled water that has circulated through the building and absorbed heat is returned to the central cooling system via the hydronic distribution system to be chilled and recirculated.

9.2.4 Hydronic Distribution Subsystem

The hydronic distribution system supplies hot and chilled water to the air distribution system to condition the supply air as well as directly to the zones when convection terminal units are used. Chapter VII covers the hydronic distribution systems which include the piping system as well as pumps and convection terminal units. For a closed hydronic distribution system the only link between the hydronic distribution system and the air distribution system is the heat transfer that takes place in the water-to-air heat exchangers located in air handling units and air terminal units. Similarly, for a closed hydronic distribution system, the link between the hydronic distribution system and the air in the zone is the convection heat transfer to the air in the zone via a convection terminal unit.

9.2.5 Air Distribution Subsystem

As discussed in Chapter VIII, the air distribution system in a large commercial or institutional building usually consists of a number of air handling units located strategically throughout the building to serve specific zones via a dedicated system of supply ducts that include duct accessories, air terminal units, and diffusers. Air handling units typically include water-to-air heat exchangers to condition the air, fans to move the air, and air cleaning devices to clean the air. The air distribution system also includes dampers to regulate air flow including the intake of outside air to maintain indoor air quality and take advantage of free cooling during times of the year when the outside air conditions permit the direct use of outside air to cool building zones.

The supply air enters each zone and is mixed with the existing air in the zone to maintain the desired temperature in the zone. As discussed earlier, this can be done using either a VAV or a constant-volume HVAC system. With a VAV system, the air is supplied at a constant temperature by the air distribution system and the airflow to the zone is varied. Conversely, with a constant-volume system the airflow to the zone is kept constant and the air distribution system varies its temperature. Air is then returned to the air-handling unit serving the zone through the return air system which consists of ducts, duct accessories, and grilles similar to the supply air system but could also include return air plenums in place of ducts in the vicinity of the zones served. Once returned, the air is either reconditioned and recirculated or exhausted to the outside via dampers.

9.2.6 Control Subsystem

The HVAC control system is the subsystem that monitors and controls all aspects of the HVAC system operation to ensure that the other four systems all work together to provide effective and efficient building conditioning. Chapter X covers HVAC control systems which can be very simple as in the case of a small commercial building using unitary equipment to very complex as in the case of a large commercial or institutional building with a central HVAC system. This is illustrated in Figure 9-1 by the centrally located control system block that is linked to all other four subsystems including the zones served by control links that interface with sensors and actuators throughout the central HVAC system to provide the system status as well as the requirements of each zone so that the system can automatically adapt and respond to changing load conditions within the building due to changes in occupancy, activity, or outside conditions.

The only sensors shown in Figure 9-1 are the thermostats in each zone. In addition to a simple thermostat, the control system might monitor the occupancy in each zone and turn the system down when no one is occupying the zone despite the thermostat setting to conserve energy. In addition, there will be a myriad of other sensors located throughout the central HVAC system such as carbon dioxide and carbon monoxide sensors to measure indoor air quality, pressure differential sensors to alert building maintenance when a filter needs to be changed, as well as sensors to monitor and measure humidity, water temperature and flow, pressure, and many others. Changes to the central HVAC system operation are affected through controllers and actuators that start fans and pumps, open and close dampers, among many other functions.

9.3 VAV SYSTEM DESCRIPTION

A variable-air-volume or VAV HVAC system maintains the desired thermal conditions in a zone by varying the airflow of the constant temperature air that is delivered to that zone. Maintaining the desired temperature in a building zone with a VAV HVAC system is similar to maintaining the temperature of bath water using the hot water valve. As the bath water cools, the temperature can be raised by opening the hot water valve and introducing more constant-temperature hot water from your water heater into the bathtub. As the new hot water mixes with the existing bath water, the temperature increases and when the temperature of the bath returns to the desired temperature the flow of hot water can either be reduced to a point where the bath temperature is maintained or shut off completely until the temperature drops below the desired temperature again.

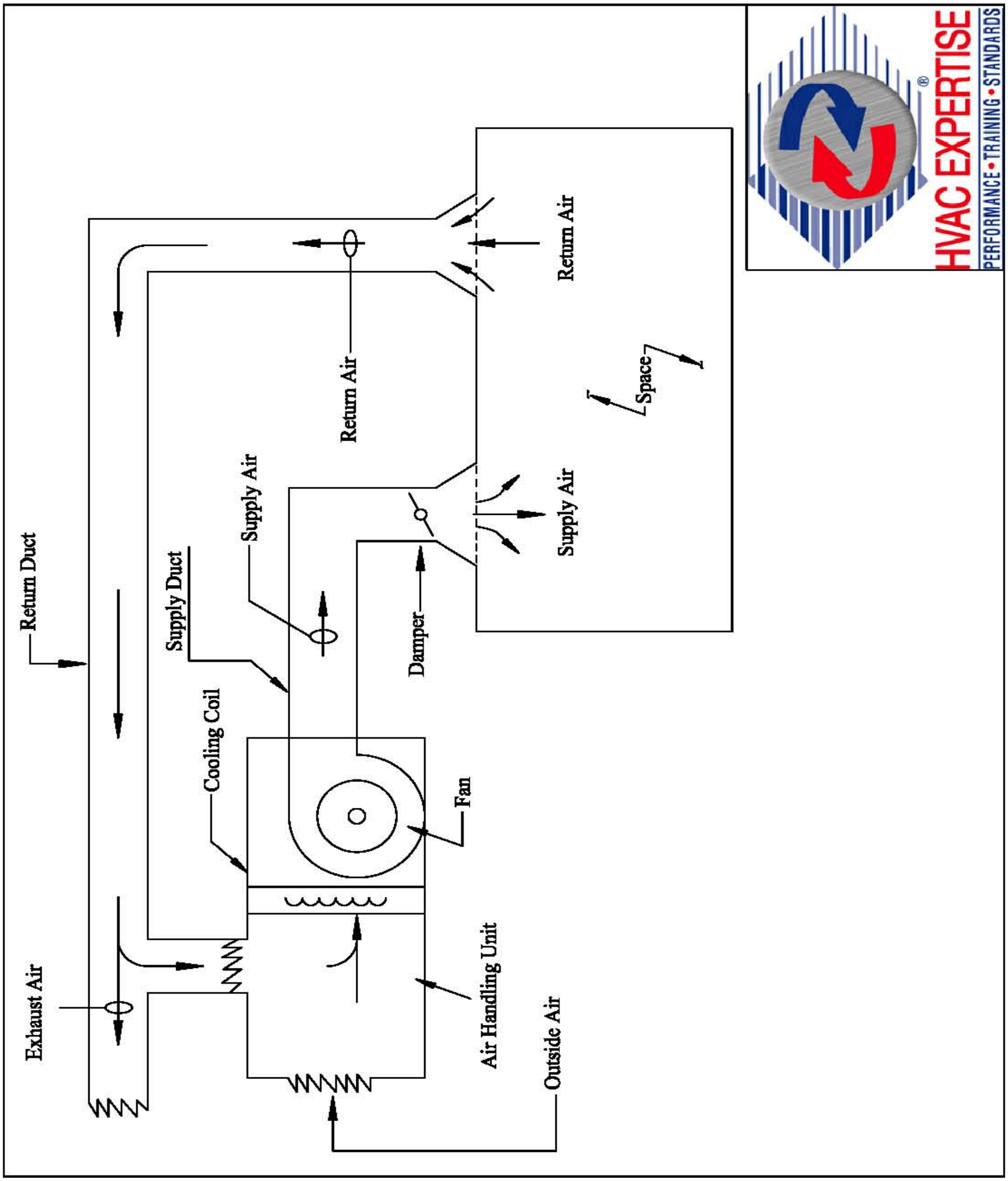
In the bath example, the hot water valve regulates the flow of hot water introduced into the bath. In VAV HVAC systems, VAV air terminal units perform the function of the valve by regulating the amount of conditioned air delivered to the zone as discussed in Chapter VIII. Instead of you sensing and manually making adjustments as you did in the bathtub, a thermostat in the zone serves as a sensor and sends a signal to the VAV terminal unit to automatically adjust the airflow if the zone temperature deviates from the desired temperature that the thermostat is set at. In a cooling-only VAV HVAC system, when the temperature in the zone increases above the thermostat setpoint a signal is sent by the thermostat that results in the VAV terminal unit delivering more cool air to the space. As the space cools, the VAV air terminal unit reduces the amount of conditioned air supplied to the space. Similarly, when the temperature drops below the thermostat setpoint the VAV terminal unit reduces the amount of cold air supplied to the zone or shuts it off completely.

9.4 VAV SYSTEM OPERATION

9.4.1 Simple Single-Zone VAV System

Figure 9-2 illustrates the operation of a basic single-zone VAV system that provides cooling only and employs a dedicated air-handling unit (AHU) to serve a single space. In Figure 9-2, space cooling is accomplished by supplying conditioned air from the dedicated AHU that consists of a cooling coil and fan. A mixture of return air and outside air is drawn across the cooling coil by the fan and cooled to the desired supply air temperature. The fan also forces the conditioned air through the supply duct and into the space. Air from the space is then returned to the AHU or exhausted to the outside through the return air duct. Return air does not have to be ducted and could be returned via a return air plenum, exhausted directly to the outside from the space, or a combination of these return air methods.

Figure 9-2 Basic Single-Zone Cooling Only VAV System



9.4.2 Adjusting Airflow

The amount of conditioned air that is supplied to the space in Figure 9-2 can be controlled in any of the following three ways:

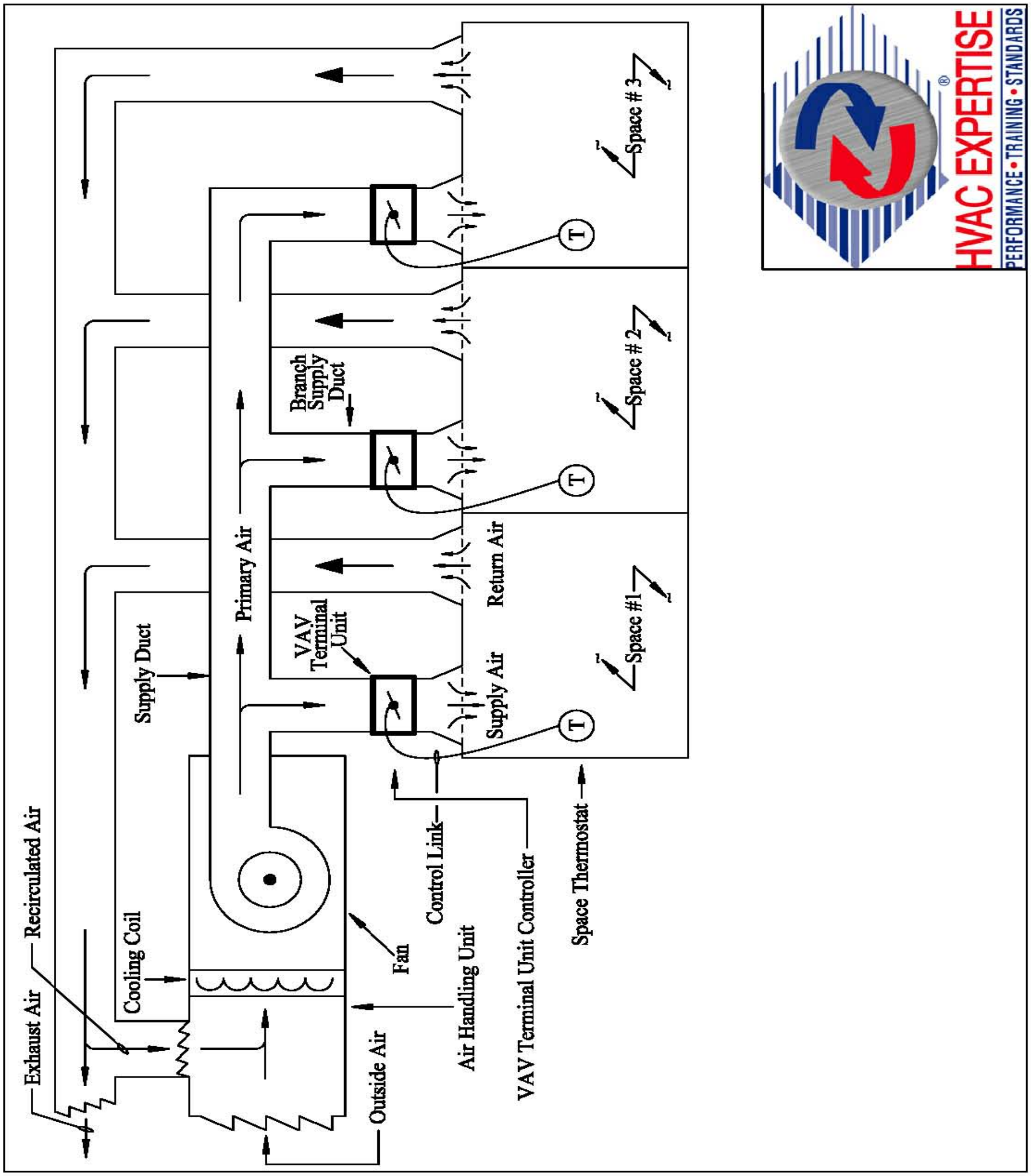
- Adjust the damper position in the supply air duct to increase or decrease the amount of conditioned air supplied to the space.
- Adjust fan airflow to increase or decrease the amount of conditioned air supplied to the space.
- Combination of these methods.

Adjusting Damper Position. Opening or closing the damper in the supply duct will result in more or less supply air being introduced into the space, respectively. If the thermal load in the space were constant, a manual damper could be installed and this damper could be adjusted once during building commissioning and never changed. Unfortunately, the thermal load in each zone is dynamic and changes constantly due to season, time of day, daily weather patterns, number of occupants, occupant activity, equipment use, and other variables. In addition, different occupants may want the space warmer or cooler depending on the activity being performed in the space. As a result, a simple manual damper will not provide the dynamic control needed to maintain thermal comfort in a building zone. In order to be effective, the damper needs to have the ability to respond automatically to changes in the zone’s thermal load. Therefore, VAV terminal units that are usually referred to simply as VAV boxes are used in place of a manual damper to control the amount of conditioned air supplied to the space. VAV terminal units automatically modulate the airflow through them in order to maintain the desired temperature of the space. VAV terminal units are an important component of VAV systems and will be discussed in detail in this chapter.

Adjusting Fan Airflow. The second way to vary the amount of conditioned air that is delivered to the space is by adjusting the fan airflow. This can be accomplished by varying the fan operating characteristics such as speed or blade pitch in response to the space’s changing thermal load. Restricting the fan inlet air supply using variable inlet vanes or blocking the fan discharge using variable discharge dampers can also be used to adjust fan airflow. Today, variable frequency drives (VFD) are used almost exclusively to adjust fan airflow because they are more efficient, require less maintenance, and are more economical in most cases when compared with other methods of adjusting fan airflow. The use of VFDs in VAV systems as well as other mechanical and electrical methods that can be used to control the supply fan airflow will be covered in this chapter.

Combination Of Methods. It should be pointed out that in the simple VAV system illustrated in Figure 9-2, the AHU only supplies one space and so varying the airflow through the fan only affects the amount of conditioned air supplied to that space. If the AHU supplies multiple spaces as shown in Figure 9-3 and each space has a different thermal load, then it is nearly impossible to ensure that each of the spaces served by the AHU will remain within its thermal comfort zone. Historically, VAV systems first attempted to control the amount of conditioned air delivered to spaces by varying the airflow through the fan but it was found that this didn’t work well for multiple zones and VAV terminal units were introduced to overcome this limitation.

Figure 9-3 Basic Multi-Zone Cooling-Only VAV System



Today, most VAV systems control the volume of air delivered to a space using both VAV terminal units at the space and vary fan speed to adjust the primary conditioned airflow based on the total demand on the AHU by all of the spaces it serves. This combination approach ensures that each space receives the supply air it needs to maintain thermal comfort under varying thermal load conditions and increases the system efficiency by allowing the supply fan to be throttled back when the system is operating at less than full load. Throttling back the supply fan in this simple system reduces electrical energy usage and avoids the need to bypass or dump primary conditioned air that is not needed when the thermal load in the spaces requires less than full fan airflow.

9.4.3 Controlling Airflow

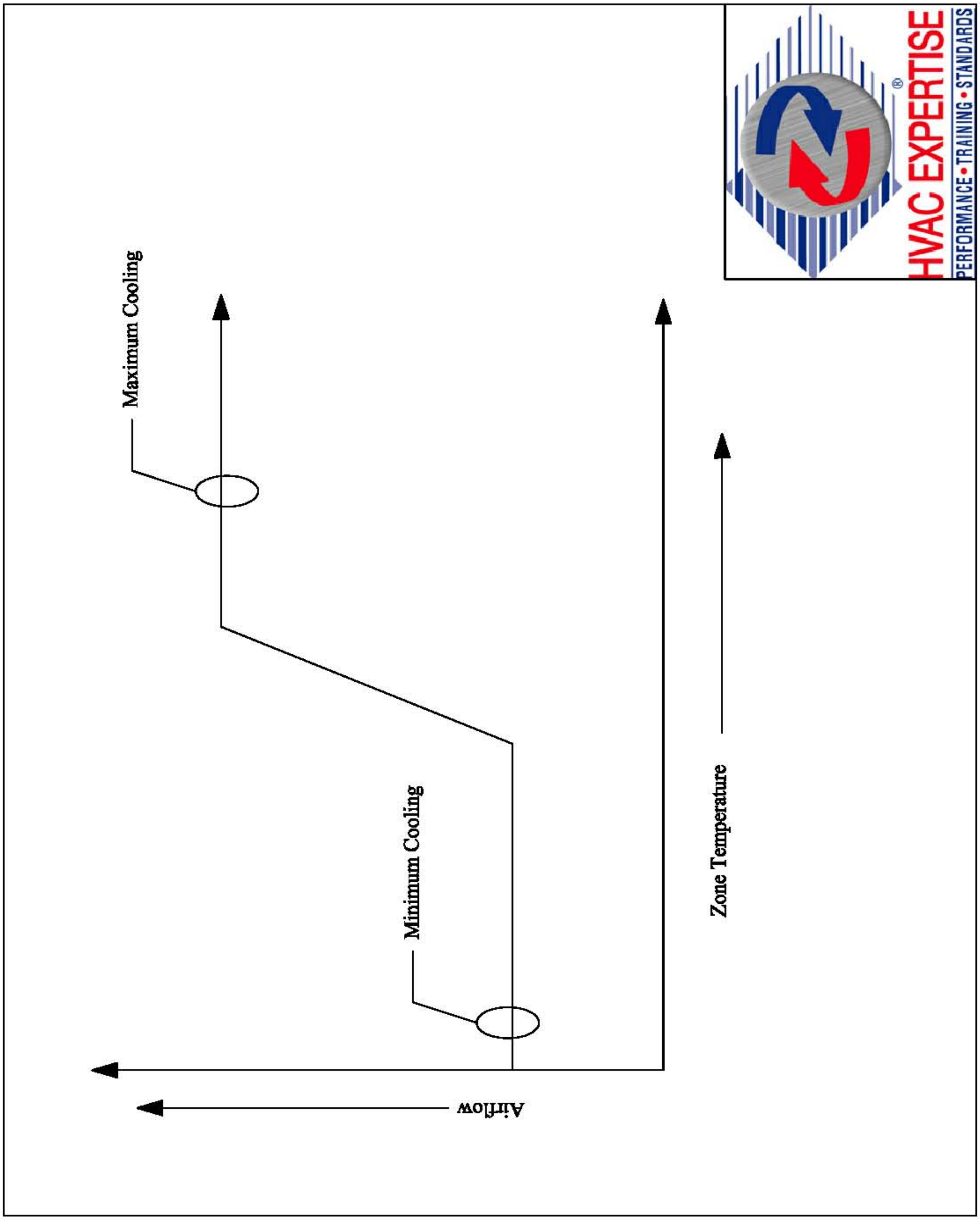
As noted above, if the thermal load in a space did not change then the damper position, fan operating characteristic, or both could be set during the system commissioning process and only adjusted as required over the life of the building. This is not the case because the thermal load is dynamic and this requires nearly constant adjustment in the amount of conditioned air supplied to the space in response to thermal load changes. The VAV system accomplishes this by monitoring selected environmental variables in a space such as temperature and adjusting the amount and characteristics of the supply air delivered to the space in response to deviations from desired conditions such as space temperature.

9.5 VAV TERMINAL UNIT OPERATION

The VAV terminal unit described and illustrated in Chapter VIII is a single-duct VAV terminal unit. This type of terminal unit is usually used on cooling-only systems where any heat needed in the zone is provided by a separate heating system or generated by the activity taking place in the space itself. For example, a single-duct VAV terminal unit could be used in the interior of an office building where people, lights, and office equipment generate needed heat.

Figure 9-4 illustrates the control scheme for a single-duct VAV terminal unit controlled by a thermostat in the zone that it serves. When the zone temperature increases above the thermostat setpoint, the terminal unit damper opens increasing the cold airflow through the terminal unit that is delivered to the zone. When the damper is fully open, the airflow is at its maximum and as can be seen from Figure 9-4, the terminal has reached its maximum cooling capability. Similarly, as the temperature in the zone drops the terminal unit damper closes to reduce the cold airflow to the zone. If the temperature in the zone continues to drop, the damper will eventually close to its minimum setting. The minimum damper setting could be fully closed which would completely cut off the cold air supply to the zone. However, the minimum damper setting is usually not fully closed as shown in Figure 9-4. The minimum damper setting is usually set to ensure minimum air movement in the zone for comfort and the introduction of a minimum amount of outside air into the zone to maintain indoor air quality.

Figure 9-4 Single-Duct VAV Terminal Unit Control Strategy



9.6 HVAC SYSTEMS INCORPORATING VAV

9.6.1 Types Of HVAC Systems Incorporating VAV

There are a number of VAV system variations that are used to achieve thermal comfort in the spaces served by the HVAC system. These VAV system variations include the following:

- Cooling-Only VAV Systems
- VAV Reheat Systems
- Dual-Duct VAV Systems
- Separate Interior & Exterior Systems

Each of these variations will be addressed in the following paragraphs.

9.6.2 Cooling-Only VAV Systems

Cooling-only VAV systems are often used in interior spaces where there are some variations in cooling loads required due to lights, people, equipment etc., but where air conditioning is needed constantly throughout the year.

9.6.3 VAV Reheat Systems

VAV terminal units can also be provided with hot water, steam, or electric reheat coils. Reheat VAV terminal units are typically used in zones that require cooling only when occupied and may need some supplemental heat when unoccupied. Reheating conditioned air supplied by the upstream air-handling unit is not an efficient method of providing needed heat to an occupied zone. When heat is required during occupancy, the cooling-only VAV system should be supplemented by another more economical method of providing zone heating such as a dual-duct VAV system or a separate heating system using convection terminal units. For example, in perimeter zones where heat is required at outside walls to counter heat loss and under windows to prevent cold down drafts, perimeter convection terminals using hot water can be installed to work in conjunction with the cooling-only VAV system.

9.6.4 Dual-Duct VAV Systems

Another type system that can handle both the interior and perimeter simultaneously is the dual-duct VAV system. A dual-duct VAV system uses dual-duct VAV terminal units that are essentially two single duct VAV terminal units combined with a mixing chamber. Cold air is supplied to one side of the dual-duct VAV terminal and hot air is supplied to the other side. The dampers in both the cold and hot side of the dual-duct VAV terminal unit are modulated and the air mixed in the mixing chamber to achieve the right temperature for delivery to the zone.

9.6.5 Separate Interior & Exterior Systems

A very common approach in building HVAC systems is to have separate interior and perimeter systems, such as a cooling-only VAV system for the interior and a heating-only or combined heating and cooling system for the perimeter. A VAV system with an independent hydronic perimeter heating system accomplishes all cooling in all zones with air while the perimeter heating system offsets the transmission heat losses but not the summer transmission heat gains.

9.7 CONSTANT VOLUME HVAC SYSTEMS

A constant volume HVAC system operates just the opposite of a VAV HVAC system. A constant volume HVAC system delivers a constant airflow to the building zones that it serves and varies the temperature of the supply air to condition the zones. To cool a zone in response to an increase in thermal load, cooler supply air is delivered at a constant airflow to mix with the existing air in the zone and lower the temperature. Similarly, when the zone requires less cooling because the thermal load has decreased, the constant volume HVAC system delivers warmer air at a constant airflow to increase the temperature of the zone.

9.8 VAV VERSUS CONSTANT-VOLUME HVAC SYSTEMS

9.8.1 VAV HVAC System Advantages

A VAV system is the preferred system for many commercial and institutional building applications when compared to a constant-volume system. Properly designed, installed, operated, and maintained, a VAV system can provide both a higher degree of building occupant comfort and significant energy savings when compared with a constant-volume system.

Constant-volume systems operate with the supply fan providing an airflow designed to accommodate building heating and cooling requirements at full design load. However, most commercial and institutional buildings rarely operate at full design load and usually operate at significantly less that full design load. Since the airflow in a Constant-volume system is constant, the supply fan horsepower requirements and the accompanying energy cost for operating the fan remain essentially constant regardless of the building HVAC load. If the constant-volume system operates for twelve to eighteen hours per day, a great deal of energy is wasted and the system is not very efficient.

On the other hand, VAV systems supply cold and sometimes hot air to building HVAC zones based on their cooling and heating needs. Since the amount of energy needed by a fan is proportional to airflow, a VAV system can significantly reduce building energy usage and costs. For example, if fan airflow could be reduced to 70 percent, the fan laws predict that the energy used by that fan will reduce to about 34 percent of the energy used if the fan operates at its rated airflow.

VAV systems are very flexible and can be reconfigured, expanded, or scaled back relatively easily depending on the building use and occupant needs. VAV terminal units are the basic building blocks of a VAV system and these units can be relocated, modified, or upgraded very easily to accommodate changing HVAC loads and air supply needs. In addition, VAV systems can address the need for any number of separate building zones because VAV systems are both modular and scalable.

Through zoning, VAV systems can simultaneously provide heating to those zones needing heating and those zones needing cooling. This feature results in increased occupant comfort throughout the building. Savings can also be achieved in sizing central heating, cooling, and air distribution equipment through zoning. Not all zones will require either maximum heating or cooling at any one time which results in diversity in the building's HVAC load. This load diversity can be taken into account when sizing central equipment for a VAV system and it may be possible to select smaller equipment than would otherwise be required for a constant-volume HVAC system. Smaller central heating, cooling, and air distribution equipment will not only result in energy savings over the life of the building but may also result in a lower HVAC system first cost.

9.8.2 Constant-Volume HVAC System Advantages

Despite the advantages of VAV systems over constant-volume systems discussed in the previous section, there are applications where constant-volume systems are the better choice over VAV systems. Constant-volume systems are generally better suited than VAV systems for applications that require a minimum number of air changes per time, positive pressure in one space in relationship to surrounding spaces, or where odor or contaminant removal is a requirement. Therefore, all of the space and occupant requirements should be considered when selecting an HVAC system and the HVAC system that best meets all of the criteria should be selected.

Where a space requires a minimum number of air changes per unit time, a constant-volume system may be the best choice for the application. When the VAV system reduces airflow to the space in response to falling temperature, the required minimum number of air changes per unit time may not be met. However, a VAV system using dual-duct VAV terminal units can provide the needed airflow under varying space temperature conditions and still provide the energy benefits of a VAV system.

Similarly, a VAV system may not be the best choice when positive pressure needs to be maintained in a space to prevent the migration of airborne contaminants such as dust from adjacent spaces. A constant-volume system delivers a constant airflow into the space that will maintain a constant pressure in the space to prevent the infiltration of airborne contaminants. Again, by its very nature a VAV system reduces airflow into a space in response to falling temperature which will necessarily result in a drop in pressure. This drop in pressure could result in the space having a negative pressure in relation to surrounding spaces and allow the infiltration of airborne contaminants into the space. However, a VAV system using either dual-duct VAV terminal units or fan-powered VAV terminal units may be able to provide constant airflow to ensure that positive pressure is maintained in the space and also take advantage of VAV system energy savings.

Again, when odor or contaminant removal is required in a space a constant-volume system may be the right choice over a VAV system. Reduced VAV system airflow in response to a falling space temperature may compromise the HVAC system's ability to remove odors and airborne contaminants from the space. However, a VAV system using either dual-duct or fan-powered VAV terminal units may be able to meet the constant airflow requirements as well as provide the energy savings associated with VAV systems.

CHAPTER X
HVAC SYSTEM CONTROL

10.1 INTRODUCTION

HVAC system control is covered in this chapter. HVAC systems seldom operate at their design point and both the external and internal thermal loads are constantly changing. The purpose of HVAC system control is to ensure that the HVAC system can effectively and efficiently adapt to changing outdoor conditions as well as changing internal occupancy and activities. This chapter starts with a discussion of the purpose of the control system followed by description of HVAC control system operation. Control loops and example control systems are then presented. Types of HVAC control systems are then discussed followed by a discussion of building automation and control. This chapter finishes with a discussion of open-architecture HVAC system control.

10.2 CONTROL SYSTEM PURPOSE

HVAC systems operate at their design point only a small fraction of the time each year. In addition, the demands on the HVAC system are changing continuously as both the outside and inside environment change. The outside environment changes with the seasons as well as hourly throughout each day which impacts the building thermal load. Similarly, the occupancy of internal spaces, equipment use, and the use of internal spaces impact the thermal load of the building. To provide a healthy and comfortable environment for building occupants to live, work, and play that is also efficient requires that the HVAC system be able to constantly adapt to changing thermal conditions. In order to adapt automatically and even to anticipate changes in thermal load, the HVAC system must have a control system that senses changes and then takes the necessary actions to adapt to the changing demands that are being placed on it. The purpose of HVAC system control is to provide an automated mechanism that ensures effective and efficient HVAC system operation under continuously changing outside and inside conditions.

10.3 CONTROL SYSTEM OPERATION

10.3.1 Control System Elements

An HVAC control system is comprised of the following seven elements:

- Controlled Process
- Controlled Variable
- Setpoint
- Sensor
- Controller
- Controlled Agent
- Controlled Device

Figure 10-1 provides a generic block diagram of an HVAC control system that that will be used to illustrate the function of each of these seven elements. A geometric shape in Figure 10-1 represents each of the above elements. Rectangles represent processes where an action is taken, rectangles with rounded ends represent sensors that measure the controlled variable, circles represent the point where a measured variable is monitored, and parallelograms represent outside input to the control process. Solid lines linking the geometric shapes represent physical relationships between the control elements and dashed lines represent signal paths where information is passed between the control elements. The following paragraphs will define and describe each of these seven elements using Figure 10-1.

10.3.2 Controlled Process

A process can be defined as a systematic operation that transforms an input to an output for a definite purpose. The quality of a process is the degree to which the output of the process meets the requirements of the people or follow-on processes using the output. The controlled process shown in Figure 10-1 is the overall HVAC system, an HVAC subsystem, a piece of HVAC equipment, or some other HVAC system device or function that is controlled by the control system. As can be seen from Figure 10-1, the controlled process is the focus of the control system.

To illustrate a controlled process in the context of an HVAC system, consider the simple block diagram of a multizone VAV HVAC system serving a zone through a VAV terminal unit shown in Figure 10-2. The controlled process in this case is the VAV terminal unit with the input being the constant temperature conditioned airflow supplied by the upstream air-handling unit and the output being the thermal comfort experienced by occupants in the zone served. The controlled process is the position of the damper within the VAV terminal unit as discussed in Section 8.7.2 and illustrated in Figure 8-11.

10.3.3 Controlled Variable

The controlled variable is the condition that the control system measures and controls. In Figure 10-1, the controlled variable is represented by the circle at the output of the controlled function. The controlled variable is the characteristic of the output of the controlled process that represents the quality of the process. The controlled variable is a characteristic of the controlled process output that is measured and controlled as an indicator of process quality. Essentially any physical attribute of the output stream that can be measured could be the controlled variable. If the controlled process is a zone in the VAV HVAC system discussed above, then controlled variable might be the measured temperature in the zone. The quality of the system output in this case might be judged based solely on the ambient temperature experienced by occupants in this zone.

Figure 10-1 Generic HVAC Control System Block Diagram

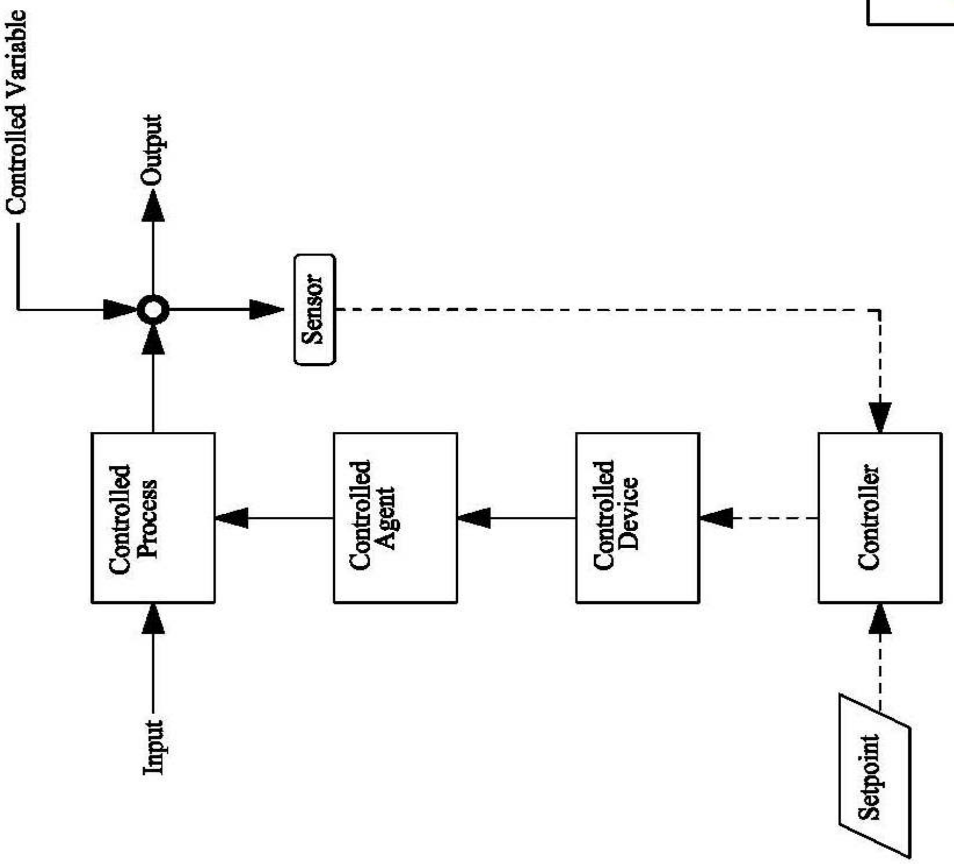


Figure 10-1 Generic HVAC Control Block Diagram Model (1)

Figure 10-2 VAV Terminal Unit Control Block Diagram

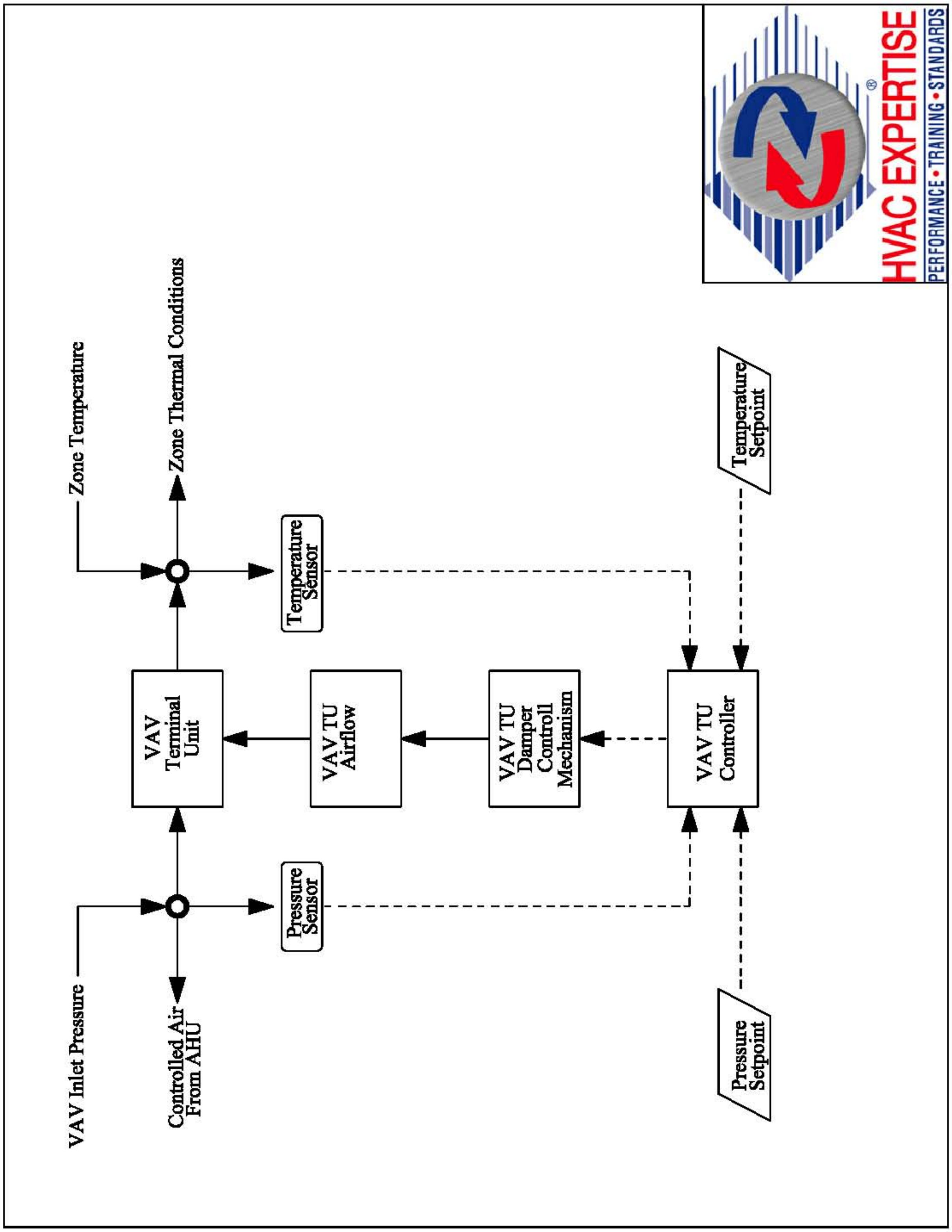


Figure 10-1 is a simple block diagram that is being used to define each of the seven elements of an HVAC control system as well as illustrate the interrelationship between the elements. For simplicity, the controlled variable is shown as a single variable measured and controlled at the output of the controlled process. In practical HVAC control schemes there may be multiple controlled variables for a single controlled process. For example, as was discussed in Section 3.5, there are actually four variables that determine human thermal comfort which are temperature, humidity, air movement, and air quality. In addition to temperature, any or all of the remaining three variables could also be measured and controlled to improve the quality of the controlled process which in this case is conditioning a zone served by a VAV HVAC system.

Besides the number of controlled variables, the location of the controlled variable in relation to the controlled process can also vary. Normally, the controlled variable will be on the output of the controlled process but it could also be at the input of the controlled process or within the controlled process itself. Using the VAV HVAC system serving a building zone as an example, the airflow through the VAV terminal unit serving the zone is determined both by the position of the internal damper and the static pressure at the input of the VAV terminal unit. As discussed in Section 8.7.3, most VAV terminal units are pressure independent and adjust the VAV terminal unit damper in response to not only the temperature in the zone served but also the static pressure at the inlet of the VAV terminal unit. As shown in Figure 10-2, the VAV terminal unit is the controlled process and the controlled variables are the temperature of the zone which represents its output and the pressure at the inlet of the VAV terminal unit.

10.3.4 Setpoint

Setpoint is the desired condition of the controlled variable. The setpoint sets the benchmark for the controlled variable and it is what the measured value of the variable is compared to determine if action is needed to achieve the desired output from the controlled process. The setpoint is usually determined during the design process for controlled variables that are a function of system or equipment capabilities, mandated codes and standards, or good design practice. An example of a controlled variable setpoint determined during the design, installation, or commissioning process might be carbon dioxide concentration in the supply air to a zone. Similarly, the setpoint could be based on output requirements during operation such as the temperature setting of the thermostat in a space. Setpoints that can be adjusted during system operation such as the temperature setting of a thermostat can be done manually or automatically based on time of day, sensed occupancy, or other factors. Similarly, commercial and institutional building control systems typically allow setpoints to be changed remotely via a building automation system (BAS).

As can be seen in Figure 10-2, the VAV terminal unit has a setpoint for both the zone temperature and the VAV terminal unit inlet pressure. The VAV terminal unit inlet pressure setpoint for this controlled process was probably set during the commissioning process and the temperature setpoint was either set manually or automatically during operation based on conditions in the zone.

10.3.5 Sensor

The sensor is the device that measures the controlled variable and sends a signal to the controller reporting the value or state of the controlled variable. Sensors can be provided for any measurable controlled variable. Among many others, sensors that are incorporated into HVAC control systems include the following:

- Temperature
- Humidity
- Flow
- Pressure
- Carbon Dioxide
- Carbon Monoxide

There are two sensors included in Figure 10-2 reflecting the fact that there are two controlled variables for the VAV terminal unit which is the controlled process in this example. At the input of the VAV terminal unit there is a pressure sensor as discussed in Section 8.7.3 and shown in Figure 8-13. This pressure sensor measures the static pressure at the inlet of the VAV terminal unit and reports that pressure to the VAV controller. In addition, there is a temperature sensor in the form of a thermostat located in the zone served by the VAV terminal unit that monitors the ambient temperature in the zone and sends a signal to the VAV controller reporting the measured temperature.

10.3.6 Controller

The controller is the processor that compares the setpoint of the controlled variable to the measured value of the controlled variable measured that is reported by the sensor. The controller compares these two values, decides what action to take based on the rules hardwired or programmed into it, and then initiates the required action by sending the appropriate signal to the controlled device.

In the VAV terminal unit example, the VAV controller receives the data sent by both the pressure and temperature sensors and processes it with the pressure and temperature setpoints to determine the action that needs to be taken by the VAV damper controller mechanism to achieve the desired zone thermal conditions that is the output of the controlled process. Once the controller determines the appropriate action that needs to be taken based on the rules hardwired or programmed into it, a signal is transmitted by the controller to the damper controller to initiate the desired action.

10.3.7 Controlled Device

The controlled device is the component that reacts to the output signal of the controller. The controlled device could be any number of control devices including but not limited to the following:

- Actuators
- Automatic Dampers
- Damper Operators
- Automatic Valves
- Valve Operators
- Contactors & Relays
- Motor Starters
- Variable Frequency Drives

In the case of the VAV terminal unit, the controlled device would be the damper control mechanism. The signal from the controller will cause the VAV terminal unit to open or close to cause increased or decreased airflow to the zone, respectively.

10.3.8 Controlled Agent

The controlled agent is the physical parameter that is manipulated by the controlled device. Manipulating the controlled agent will in turn impact the output of the controlled process to achieve the desired process outcome. In the case of the VAV terminal unit example shown in Figure 10-2, the controlled agent is the airflow through the VAV terminal unit into the zone. Varying the airflow of the constant temperature air supply will maintain the desired temperature in the zone. Other controlled agents might be the volumetric flow rate of chilled or hot water circulated through a coil in an air-handling unit, the airflow through a damper, among other HVAC system physical parameters.

10.4 CONTROL LOOPS

10.4.1 Control Loop Defined

The following four elements shown in Figure 10-1 make up a physical control loop:

- Sensor
- Controller
- Controlled Device
- Controlled Agent

As discussed previously, the sensor is the device that continuously monitors the controlled variable and transmits the value or state of the controlled variable back to the controller. The controller compares the value or state of the controlled variable to the setpoint and when there is a difference determines the action to be taken based on a set of rules that are hardwired or programmed into it. The controller then initiates the action to be taken by sending a signal to the controlled device. The controlled device then changes its state in response to the controller signal and causes a change to the controlled agent. The change in the controlled agent will then impact the output of the controlled process that in turn will be monitored by the sensor and the whole cycle or loop begins again. This control loop is illustrated schematically in Figure 10-3.

10.4.2 Types Of Control Loops

There are two types of control loops used in HVAC systems. These two types of control loops are as follows:

- Closed Loop Control
- Open Loop Control

The following paragraphs will discuss each of these control loops and how they are used in HVAC systems.

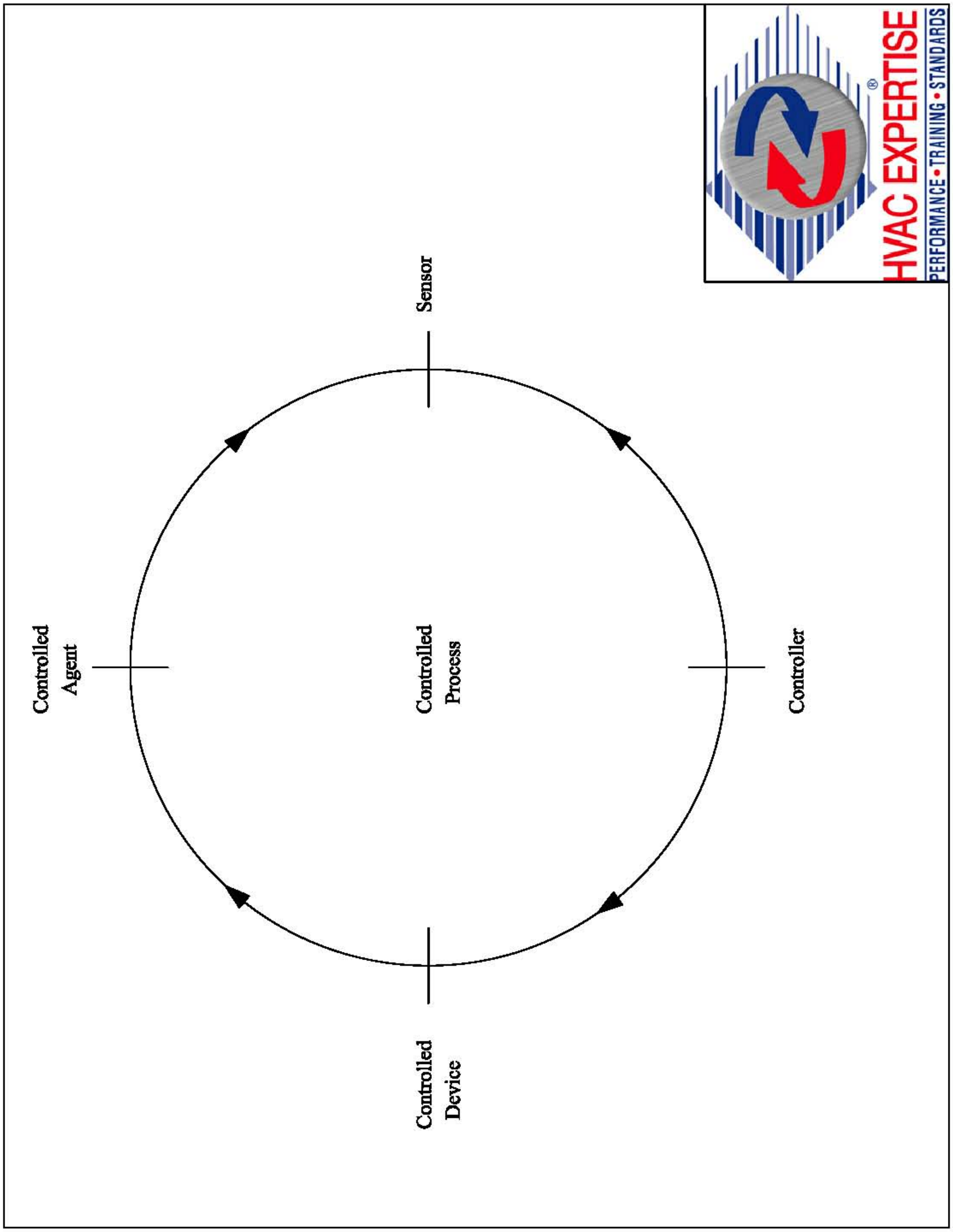
10.4.3 Closed Loop Control Systems

The control system block diagrams shown in both Figures 10-1 and 10-2 are closed loop control systems. In a closed loop control system, the controller measures actual changes in the controlled variable via the sensor and initiates action through the controlled device to bring the actual system output in line with the desired system output as defined by the controlled variable setpoint. The corrective action is a continuous process as shown in Figure 10-3 that continues until the controlled variable is brought to the desired value within the design limitations of the controller. With a closed loop control system, the results of the action taken by the controller are continually monitored by the sensor and fed back to the controller for further action and is referred to as feedback.

10.4.4 Open Loop Control Systems

An open loop control system differs from a closed loop control systems in that an open loop control system usually takes corrective action to offset the impact of an external change to a controlled variable. Open loop control systems are also referred to as feed-forward control systems because there is no feedback mechanism like there is with a closed loop control systems. An example of an open loop or feed-forward control system would be the use of an outside thermostat that measures outdoor temperatures to adjust the operation of the building’s HVAC system. In this case, the outside thermostat is the sensor controlling the HVAC system and the inside temperature of the building is not part of the control loop. There are instances where open loop control systems are used in HVAC systems but to be effective these open loop control systems are integrated with closed loop control systems to ensure that changes made by the controlled agent actually provide the desired output from the controlled process.

Figure 10-3 Control Loop



10.4.5 Closed Loop HVAC Control System Example

Figure 10-4 provides an example of a closed loop HVAC control system involving the control of the supply air temperature through a cooling coil in an air-handling unit. The temperature probe in Figure 10-4 is the control system sensor. The temperature probe senses the temperature of the supply air passing through the cooling coil and transmits the temperature to the controller. The controller compares the actual supply air temperature with the desired supply air temperature which is the setpoint input to the controller. The controller sends a control signal to the valve which is the controlled device and instructs it to either open or close based on whether the sensed temperature in the air stream is higher than the setpoint or lower than the setpoint, respectively. In this example, the controlled agent is the chilled water where increasing the flow of chilled water through the cooling coil will reduce the temperature of the supply air and decreasing the flow of chilled water through the coil will increase the temperature of the supply air.

10.5 THERMOSTAT: SIMPLE CONTROL SYSTEM

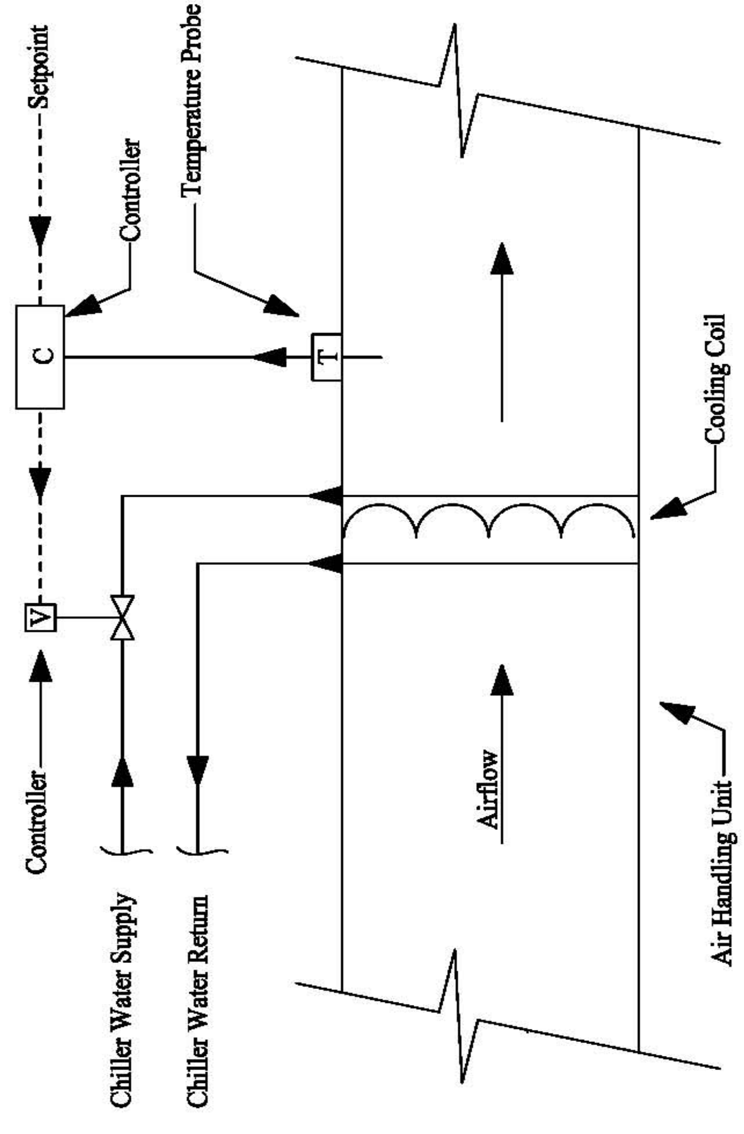
Up until now, the sensor, controller, and controlled device were shown as separate devices. In some cases two or more of these devices will be integrated together in a single unit. An example of a case when all three of these devices are integrated together into a single unit is a simple residential or light commercial thermostat that controls a unitary HVAC system directly by simply turning it on or off. A simple wall-mounted thermostat contains a temperature sensor which represents the sensor, has provisions for setting the thermostat at the desired temperature which is the setpoint, contains the controller which compares the setpoint and measured temperature and initiates the needed corrective action through the controlled device which is simply a set of normally open contacts in the thermostat. Closing those contacts causes the air conditioner or furnace to start up and supply the needed cooling or heating to bring the ambient temperature in the home or light commercial building or space in line with the desired temperature.

10.6 TYPES OF CONTROL SYSTEMS

10.6.1 Control System Types

As noted previously, the dashed lines connecting the sensor to the controller and the controller to the controlled device in Figures 10-1 and 10-2 represent control signal paths that allow information to be passed between devices. The value or state of the control variable is sensed by the sensor and transmitted to the controller. The controller processes the information sent by the sensor with the controlled variable setpoint and transmits a signal indicating the desired action to the controlled device. The method used to transmit information and control signals in HVAC control systems often is used to describe the type of control system used. Over time the methods used to transmit control information and signals has changed with advancing technology.

Figure 10-4 HVAC Closed Loop Control System



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The four primary methods that have been used to transmit information and control signals in HVAC systems are as follows:

- Pneumatic Control
- Analog Electric Control
- Analog Electronic Control
- Direct Digital Control

Direct digital control is used almost exclusively in today's HVAC systems in commercial and institutional buildings. However, existing HVAC systems still use pneumatic, analog electric, and analog electronic control systems. The following paragraphs will discuss each of these control systems.

10.6.2 Pneumatic Control

The first HVAC control systems were pneumatic normally using compressed air to transmit information and control signals. Pneumatic control systems often used compressed air to directly initiate a change in the controlled device and did not require a transducer to convert the digital signal into an electromechanical action. Pneumatic controls are capable of measuring changes in the controlled variable using pneumatic sensors and transmitting the measured changes to the pneumatic controller. Pneumatic logic within the controller could be used to process the inputs received from sensors and produce an output that would signal the action that the controlled device should take. Pneumatic HVAC controls were reliable but were difficult to calibrate, were not as accurate as today's direct digital controls, and also required regular maintenance.

10.6.3 Analog Electric Or Electronic Control

Analog electric and electronic controls followed pneumatic controls. The difference between analog electric and electronic control was that the signal sent by analog electric controls usually had sufficient power to cause a change in the controlled device's state directly. Analog electronic controls like direct digital controls usually required a transducer to convert the control signal to a pneumatic or electric signal with enough power to change the state of the controlled device.

10.6.4 Direct Digital Control

Direct digital control or DDC control systems have almost totally replaced pneumatic, analog electric, and analog electronic control systems in commercial and institutional buildings. Direct digital control systems are microprocessor-based systems that use digital logic to transmit control system information and signals. Direct digital control systems always need a transducer to convert the digital control signal sent by the controller to affect the change in the controlled device. However, in most cases this transducer is built into the controlled device and a separate transducer is not needed.

One of the advantages of direct digital control is that these systems are both low power and low voltage allowing control cabling to be run throughout the building without being enclosed in raceway. However, when installed in plenums the cable must be plenum rated. The cable used today to interconnect devices is often unshielded twisted pair (UTP) copper cable that is used also for other building structured cabling systems such as local area networks (LANs), life safety and security systems, and other voice/data/video applications. Hardwired connections using UTP are most common however some systems will allow the use of wireless communications between devices using WiFi, Bluetooth, and ZigBee technologies, power over Ethernet (POE), optical fiber cable, or powerline carrier.

10.7 BUILDING AUTOMATION & CONTROL SYSTEMS

Direct digital control has led to the development and widespread use of building automation and control systems (BAS). These computer-based control systems control the building's HVAC system from a central location and are increasingly integrated with the building lighting control system, life safety and security system, voice/data/video systems, and other related building systems. Building automation and control systems are networked systems where there is a central station that monitors and controls the overall system from one location as well as stores data on system operation. Networked with the central station are intelligent remote building automation and control panels and equipment that are capable of operating independently of the central station. In addition, many of these building automation and control systems also have the capability of being remotely monitored and controlled over the Internet allowing centralized monitoring and control of HVAC, refrigeration, lighting, life safety and security, and other building systems by owners with multiple properties around the city, region, county, or world. In addition to simply monitoring and controlling the HVAC system, these building automation and control systems allow the owner to change setpoints and setup schedules of operation, trend logs, alarms, and other reporting features as required.

10.8 OPEN-ARCHITECTURE CONTROL SYSTEMS

10.8.1 What Is An Open-Architecture Control System?

An open-architecture control system is one where the hardware and software specifications are in the public domain and available to anyone that wants to design and manufacture hardware components or develop software tools that will operate with the system. This is in contrast to closed-architecture control systems where the original system developer maintains control of the system specifications and is the only entity that can design and manufacture components or develop software tools for the system. Proprietary or closed-architecture control systems have been the norm in the building industry with each building system being treated as an independent system and having its own standalone control system. Integration and interoperability between proprietary system-specific building control systems is difficult.

The trend today is to view buildings not as a group of independent systems that need to be individually optimized but a collection of interdependent subsystems that need to be optimized collectively in order to provide an efficient building that addresses the needs of its occupants. An open-architecture system is best suited to provide the flexibility and interoperability that building owners and occupants are seeking today. Integrating subsystems and optimizing the building as a whole results in increased building efficiency and a better environment for occupants that translates into a healthier and more productive atmosphere for occupants to live, work, and play.

10.8.2 Advantages Of Open-Architecture Control Systems

In addition to more readily allowing various building systems to be integrated and the building operation optimized as a whole, an open-architecture control system offers building owners a number of other advantages beyond operational efficiency including the following:

- Allows for a multi-vendor system that permits system integrators to select control devices that are best for the application.
- Allows incorporation of any system into the overall open-architecture control system including lighting, life safety and security, and other systems that may not be possible with proprietary systems.
- Allows for competitive bidding not only for the initial installation but also more importantly for service over the life of the system. Future system expansions and upgrades as well as everyday moves, adds, and changes can be negotiated or competitively bid because the owner is no longer locked into a single proprietary system.
- Allows for system service to be performed by any qualified firm and the owner is no longer locked into the supplier of the proprietary system for service over the life of the system.
- Allows the system to be upgraded using the latest technology control devices from any vendor whose devices are compatible with the open-architecture control system and the owner is not locked into the speed at which the proprietary control system supplier decides to adopt new technology.
- Allows legacy proprietary control systems and components in existing buildings to be integrated into open-architecture control systems through system gateways and individual device interfaces.

10.8.3 Open-Architecture Control Standards

There are two dominant open-architecture control standards used in North America today and these standards are:

- BACnet
- LonWorks

BACnet Control Standard. The BACnet standard was developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to provide an open-architecture control standard for building mechanical systems and equipment. BACnet stands for "building automation and control network" and is an American National Standards Institute (ANSI) approved standard. The BACnet standard is designated ANSI/ASHRAE 135-2004 and entitled *BACnet – A Data Communication Protocol for Building Automation and Control Networks*. Even though BACnet could be used for other systems, its use has been limited to mainly mechanical systems and equipment which it was designed for.

LonWorks Control Standard. LonWorks-compatible control devices communicate with each other using the ANSI approved standard that was originally developed by Echelon Corporation and adopted by the Electronics Industry Association (EIA) and Consumer Electronics Association (CEA) as EIA/CEA 709.1-B-2002 entitled *Control Network Protocol Specification*. LonTalk is the communications protocol based on EIA/CIA 709.1-B-2002 that allows LonWorks-compatible control devices to communicate based on the Open Systems Interconnection (OSI) seven-layer reference model for peer-to-peer network communications.

The heart of the LonWorks system is the Neuron chip that is produced by Echelon and implements the lower six layers of the OSI reference models. This leaves only the seventh layer which is the application protocol that needs to be dealt with when implementing a LonWorks control system. Each Neuron chip is assigned a unique permanent 48-bit code for addressing that is referred to as the Neuron ID. Manufacturers of LonWorks compatible devices then embed neuron chips along with input/output (I/O) devices and application programming to run the chip so each controlled device has a unique system address.

APPENDIX A
HVAC GLOSSARY

Absolute Pressure: Air at standard conditions (70°F air at sea level with a barometric pressure of 29.92 in.Hg.) exerts a pressure of 14.696 psi. This is the pressure in a system when the pressure gauge reads zero. So the absolute pressure of a system is the gauge pressure in pounds per square inch added to the atmospheric pressure of 14.696 psi (use 14.7 psi in environmental system work) and the symbol is "psia."

Absorbent: A material which, due to an affinity for certain substances, extracts one or more such substances from a liquid or gaseous medium with which it contacts and which changes physically or chemically, or both, during the process. Calcium chloride is an example of a solid absorbent, while solutions of lithium chloride, lithium bromide, and ethylene glycols are liquid absorbents.

Adiabatic Process: A thermodynamic process during which no heat is added to, or taken from, a substance or system.

Adsorbent: A material which has the ability to cause molecules of gases, liquids, or solids to adhere to its internal surfaces without changing the adsorbent physically or chemically. Certain solid materials, such as silica gel and activated alumina, have this property.

Air, Ambient: Generally speaking, the air surrounding an object. .

Air, Dry: Air without contained water vapor; air only.

Air, Outdoor: Air taken from outdoors and, therefore, not previously circulated through the system.

Air, Recirculated: Return air passed through the conditioner before being again supplied to the conditioned space.

Air, Reheating of: In an air conditioning system, the final step in treatment, in the event the temperature is too low.

Air, Return: Air returned from conditioned space.

Air, Saturated: Moist air in which the partial pressure of the water vapor is equal to the vapor pressure of water at the existing temperature. This occurs when dry air and saturated water vapor coexist at the same dry-bulb temperature.

Air, Standard: Dry air at a pressure of 29.92 in. Hg at 69.8°F temperature and with a specific volume of 13.33 ft.^{3}/lb.

Air Changes: A method of expressing the amount of air leakage into or out of a building or room in terms of the number of building volumes or room volumes exchanged.

Air Conditioner, Unitary: An evaporator, compressor, and condenser combination; designed in one or more assemblies, the separate parts designed to be assembled together.

Air Conditioning, Comfort: The process of treating air so as to control simultaneously its temperature, humidity, cleanliness and distribution to meet the comfort requirements of the occupants of the conditioned space.

Air Conditioning Unit: An assembly of equipment for the treatment of air so as to control, simultaneously, its temperature, humidity, cleanliness and distribution to meet the requirements of a conditioned space.

Air Diffuser: A circular, square, or rectangular 'air distribution outlet, generally located in the ceiling and comprised of deflecting members discharging supply air in various directions and planes, and arranged to promote mixing of primary air with secondary room air.

Air Washer: A water spray system or device for cleaning, humidifying, or dehumidifying the air.

Barometer: Instrument for measuring atmospheric pressure.

Boiling Point: The temperature at which the vapor pressure of a liquid equals the absolute external pressure at the liquid-vapor interface.

British Thermal Unit (Btu): The Btu is defined as the heat required to raise the temperature of a pound of water from 59° to 60°F.

Bulb: The name given to the temperature sensing device located in the fluid for which control or indication is provided. The bulb may be liquid-filled, gasfilled, or gas-and-liquid filled. Changes in temperature produce pressure changes within the bulb which are transmitted to the controller.

Bypass: A pipe or duct, usually controlled by valve or damper, for conveying a fluid around an element of a system.

Ceiling Outlet: A round, square, rectangular, or linear air diffuser located in the ceiling which provides a horizontal distribution pattern of primary and secondary air over the occupied zone and induces low velocity secondary air motion through the occupied zone.

Celsius (Formerly Centigrade): A thermometric scale in which the freezing point of water is called O°C and its boiling point 100°C at normal atmospheric pressure (14.696 psi).

Change of State: Change from one phase, such as solid, liquid or gas, to another.

Changeover: The process of switching an air conditioning system from heating to cooling, or vice versa.

Coefficient of Performance (COP), Heat Pump: The ratio of the compressor heating effect (heat pump) to the rate of energy input to the shaft of the compressor, in consistent units, in a complete heat pump, under designated operating conditions.

Coil: A cooling or heating element made of pipe or tubing.

Cold Deck: The cooling section of a mixed air zoning system.

Combustion: The act or process of burning.

Comfort Chart: A chart showing effective temperatures with dry-bulb temperatures and humidities (and sometimes air motion) by which the effects of various air conditions on human comfort may be compared.

Comfort Cooling: Refrigeration for comfort as opposed to refrigeration for storage or manufacture.

Comfort Zone: (Average) the range of effective temperatures over which the majority (50 percent or more) of adults feels comfortable; (extreme) the range of effective temperatures over which one or more adults feel comfortable.

Compressor: The pump which provides the pressure differential to cause fluid to flow and in the pumping process increases pressure of the refrigerant to the high side condition. The compressor is the separation between low side and high side.

Condensate: The liquid formed by condensation of a vapor. In steam heating, water condensed from steam; in air conditioning, water extracted from air, as by condensation on the cooling coil of a refrigeration machine.

Condensation: Process of changing a vapor into liquid by extracting heat. Condensation of steam or water vapor is effected in either steam condensers or dehumidifying coils, and the resulting water is called condensate.

Condenser: The heat exchanger in which the heat absorbed by the evaporator and some of the heat of compression introduced by the compressor are removed from the system. The gaseous refrigerant changes to a liquid, again taking advantage of the relatively large heat transfer by the change of state in the condensing process.

Conditions, Standard: A set of physical, chemical, or other parameters of a substance or system which defines an accepted reference state or forms a basis for comparison.

Conductance, Thermal: Time rate of heat flow through a body (frequently per unit area) from one of its bounding surfaces to the other for a unit temperature difference between the two surfaces, under steady **conditions.**

Conductivity, Thermal: The time rate of heat flow through unit area and unit thickness of a homogeneous material under steady conditions when a unit temperature gradient is maintained in the direction perpendicular to area. Materials are considered homogeneous when the value of the thermal conductivity is not affected by variation in thickness or in size of sample within the range normally used in construction.

Conductor, Thermal: A material which readily transmits heat by means of conduction.

Control Diagram (ladder diagram): A diagram that shows the control scheme only. Power wiring is not shown. The control items are shown between two vertical lines; hence, the name-ladder diagram.

Control Point: The value of the controlled variable which the controller operates to maintain.

Controlled Device: One which receives the converted signal from the transmission system and translates it into the appropriate action in the environmental system. For example: a valve opens or closes to regulate fluid flow in the system.

Controller: An instrument which receives the signal from the sensing device and translates that signal into the appropriate corrective measure. The correction is then sent to the system controlled devices through the transmission system.

Convection: Transfer of heat by movement of fluid. Convection, Forced: Convection resulting from forced circulation of a fluid, as by a fan, jet or pump.

Cooling, Evaporative: Involves the adiabatic exchange of heat between air and water spray or wetted surface. The water assumes the wet-bulb temperature of the air, which remains constant during its traverse of the exchanger.

Cooling Coil: An arrangement of pipe or tubing which transfers heat from air to a refrigerant or brine.

Cycle: A complete course of operation of working fluid back to a starting point, measured in thermodynamic terms (functions). Also in general for any repeated process on any system.

Cycle, Reversible: Theoretical thermodynamic cycle, composed of a series of reversible processes, which can be completely reversed.

Damper: A device used to vary the volume of air passing through an air outlet, air inlet or duct.

Deadband: In HVAC, a temperature range in which neither heating nor cooling is turned on; in load management, a kilowatt range in which loads are neither shed nor restored.

Dehumidification: The condensation of water vapor from air by cooling below the dewpoint or removal of water vapor from air by chemical or physical methods.

Dehumidifier: (1) An air cooler or washer used for lowering the moisture content of the air passing through it; (2) An absorption or adsorption device for removing moisture from air.

Density: The ratio of the mass of a specimen of a substance to the volume of the specimen. The mass of a unit volume of a substance. When weight can be used without confusion, as synonymous with mass, density is the weight per unit volume.

Desiccant: Any absorbent or adsorbent, liquid or solid, which will remove water or water vapor from a material. In a refrigeration circuit, the desiccant should be insoluble in the refrigerant.

Dew Point Temperature: The temperature at which moist air becomes saturated (100% relative humidity) with water vapor when cooled at constant pressure .

Differential: The difference between the points where a controller turns "on" and "off." If a thermostat turns a furnace on at 68° and the differential is 3°, the burner will be turned off at 71°.

Diffuser: A circular, square, or rectangular air distribution outlet, generally located in the ceiling and comprised of deflecting members discharging supply air in various directions and planes, and arranged to promote mixing of primary air with secondary room air.

Drift: Term used to describe the difference between the set point and the actual operating or control point.

Droop: Terms used to describe the difference between the set point and the actual operating or control point.

Dry Bulb Temperature: The temperature registered by an ordinary thermometer. The dry bulb temperature represents the measure of sensible heat, or the intensity of heat.

Duct: A passageway made of sheet metal or other suitable material, not necessarily leak tight, used for conveying air or other gas at low pressures.

Dust: An air suspension (aerosol) or particles of any solid material, usually with particle size less than 100 microns.

Economizer: A system of dampers, temperature and humidity sensors, and motors which maximizes the use of outdoor air for cooling.

Enthalpy: The total quantity of heat energy contained in a substance, also called *total heat;* the thermodynamic property of a substance defined as the sum of its internal energy plus the quantity Pv/J, where P = pressure of the substance, v = its volume, and J = the mechanical equivalent of heat.

Enthalpy, Specific: A term sometimes applied to enthalpy per unit weight.

Entropy: The ratio of the heat added to a substance to the absolute temperature at which it is added.

Entropy, Specific: A term sometimes applied to entropy per unit weight.

Evaporation: Change of state from liquid to vapor. Evaporative Cooling: The adiabatic exchange of heat between air and a water spray or wetted surface. The water approaches the wet-bulb temperature of the air, which remains constant during its traverse of the exchanger.

Evaporator: The heat exchanger in which the medium being cooled, usually air or water, gives up heat to the refrigerant through the exchanger transfer surface. The liquid refrigerant boils into a gas in the process of the heat absorption.

Fahrenheit: A thermometric scale in which 32 ^{o}F denotes freezing and 212 ^{o}F the boiling point of water under normal pressure at sea level (14.696 psi).

Fan, Centrifugal: A fan rotor or wheel within a scroll type housing and including driving mechanism supports for either belt drive or direct connection.

Fan Performance Curve: Fan performance curve refers to the constant speed performance curve. This is a graphical presentation of static or total pressure and power input over a range of air volume flow rate at a stated inlet density and fan speed. It may include static and mechanical efficiency curves. The range of air volume flow rate which is covered generally extends from shutoff (zero air volume flow rate) to free delivery (zero fan static pressure). The pressure curves are generally referred to as the pressure-volume curves.

Fan Propeller: A propeller or disc type wheel within a mounting ring or plate and including driving mechanism supports for either belt drive or direct connection.

Fan, Tubeaxial: A propeller or disc type wheel within a cylinder and including driving mechanism supports for either belt drive or direct connection.

Fan, Vaneaxial: A disc type wheel within a cylinder, a set of air guide vanes located either before or after the wheel and including driving mechanism supports for either belt drive or direct connection.

Filter: A device to remove solid material from a fluid.

Fluid: Gas, vapor, or liquid.

Freezing Point: Temperature at which a given liquid substance will solidify or freeze on removal of heat. Freezing point of water is 32°F.

Grains of Moisture: The unit of measurement of actual moisture contain~d in a sample of air. (7000 grains = one pound of water).

Gravity, Specific: Density compared to density of standard material; reference usually to water or to air.

Grille: A louvered or perforated covering for an air passage opening which can be located on a wall, ceiling or floor.

Heat: The form of energy that is transferred by virtue of a temperature difference.

Heat, Latent: Change of enthalpy during a change of state, usually expressed in Btu per lb. With pure substances, latent heat is absorbed or rejected at constant pressure.

Heat, Sensible: Heat which is associated with a change in temperature; specific heat exchange of temperature; in contrast to a heat interchange in which a change of state (latent heat) occurs.

Heat, Specific: The ratio of the quantity of heat required to raise the temperature of a given mass of any substance one degree to the quantity required to raise the temperature of an equal mass of a standard substance (usually water at 59° F) one degree.

Heat, Total (Enthalpy): The sum of sensible heat and latent heat between an arbitrary datum point and the temperature and state under consideration.

Heat Capacity: The amount of heat necessary to raise the temperature of a given mass one degree. Numerically, the mass multiplied by the specific heat.

Heat Exchanger: A device specifically designed to transfer heat between two physically separated fluids.

Heat of Fusion: Latent heat involved in changing between the solid and the liquid states.

Heat of Vaporization: Latent heat involved in the change between liquid and vapor states.

Heating, Regenerative (or Cooling): Process of utilizing heat, which must be rejected or absorbed in one part of the cycle, to perform a useful function in another part of the cycle by heat transfer.

High Limit Control: A device which normally monitors the condition of the controlled medium and interrupts system operation if the monitored condition becomes excessive.

High Pressure Cutout: A pressure actuated switch to protect the compressor from pressure often caused by high condenser temperatures and pressure due to fouling and lack of water or air.

Horsepower: Unit of power in foot-pound-second system; work done at the rate of 550 ft-lb per sec, or 33,000 ft-lb per min.

Hot Deck: The heating section of a multizone system.

Humidifier: A device to add moisture to air. Humidifying Effect: The latent heat of vaporization of water at the average evaporating temperature times the weight of water evaporated per unit of time.

Humidistat: A regulatory device, actuated by changes in humidity, used for the automatic control of relative humidity.

Humidity: Water vapor within a given space. Humidity, Absolute: The weight of water vapor per unit volume .

Humidity, Percentage: The ratio of the specific humidity of humid air to that of saturated air at the same temperature and pressure, usually expressed as a percentage (degree of saturation; saturation ratio).

Humidity Ratio: The ratio of the mass of the water vapor to the mass of dry air contained in the sample.

Humidity, Relative: The ratio of the mol fraction of water vapor present in the air, to the mol fraction of water vapor present in saturated air at the same temperature and barometric pressure; approximately, it equals the ratio of the partial pressure or density of the water vapor in the air, to the saturation pressure or density, respectively, of water vapor at the same temperature.

Humidity, Specific: Weight of water vapor (steam) associated with 1 lb. weight of dry air, also called humidity.

Hunting: A condition which occurs when the desired condition cannot be maintained. The controller, controlled device and system, individually or collectively, continuously override or "overshoot" the control point with a resulting fluctuation and loss of control of the condition to be maintained.

Inch of Water (in. w.g.): A unit of pressure equal to the pressure exerted by a column of liquid water 1 inch high at a temperature of 39.2 °F.

Isentropic: An adjective describing a reversible adiabatic process; a change taking place at constant entropy.

Isobaric: An adjective used to indicate a change taking place at constant pressure.

Isothermal: An adjective used to indicate a change taking place at constant temperature.

Latent Heat: The amount of heat necessary to change a quantity of water to water vapor without changing either temperature or pressure. When water is vaporized and passes into the air, the latent heat of vaporization passes into the air along with the vapor. Likewise, latent heat is removed when water vapor is condensed.

Load: The amount of heat per unit time imposed on a refrigerant system, or the required rate of heat removal.

Louver: An assembly of sloping vanes intended to permit air to pass through and to inhibit transfer of water droplets.

Low Limit Control: A device which normally monitors the condition of the controlled medium and interrupts system operation if the monitored condition drops below the desired minimum value.

Manometer: An instrument for measuring pressures: especially a U-tube partially filled with a liquid, usually water, mercury, or a light oil, so constructed that the amount of displacement of the liquid indicates the pressure being exerted on the instrument.

Melting Point: For a given pressure, the temperature at which the solid and liquid phases of the subsance are in equilbrium.

Modulation: Of a control, tending to adjust by increments and decrements.

Modulating Control: A mode of automatic control in which the action of the final control element is proportional to the deviation, from set point, of the controlled medium.

Modulating Controllers: Constantly reposition themselves in proportion to the requirements of the system, theoretically being able to maintain an accurately constant condition.

N.C.: *Normally closed* contacts of a relay. Contacts are close-circuited when the relay is de-energized.

N.O.: *Normally open* contacts of a relay. Contacts are open-circuited when relay is deenergized.

Normally open (or Normally closed): The position of a valve, damper, relay contacts, or switch when external power or pressure is *not* being applied to the device. Valves and dampers usually are returned to a "normal" position by a spring.

"On-off" Control: A two-position action that allows operation at either maximum or minimum condition, or on or off, depending on the position of the controller.

Operating Point: The value of the controlled condition at which the controller actually operates. Also called control point.

Optimum Operative Temperature: Temperature that satisfies the greatest possible number of people at a given clothing and activity level.

Outlet, Ceiling: A round, square, rectangular, or linear air diffuser located in the ceiling, which provides a horizontal distribution pattern of primary and secondary air over the occupied zone and induces low velocity secondary air motion through the occupied zone.

Pneumatic: Operated by air pressure. Pneumatic-Electric (PE) Switches: Device that operates an electric switch from a change of air pressure.

Point, Critical: Of a substance, state point at which liquid and vapor have identical properties; critical temperature, critical pressure, and critical volume are the terms given to the temperature, pressure, and volume at the critical point. Above the critical temperature or pressure, there is no demarcation line between liquid and gaseous phases.

Pressure: The normal force exerted by a homogeneous liquid or gas, per unit of area, on the wall of its container.

Pressure, Absolute: Pressure referred to that of a perfect vacuum. It is the sum of gauge pressure and atmospheric pressure.

Pressure, Atmospheric: It is the pressure indicated by a barometer. Standard atmosphere is the pressure equivalent to 14.696 psi or 29.921 in. of mercury at 32°F.

Pressure, Critical: Vapor pressure corresponding to the substance's critical state at which the liquid and vapor have identical properties.

Pressure, Static (SP): The normal force per unit area that would be exerted by a moving fluid on a small body immersed in it if the body were carried along with the fluid. Practically, it is the normal force per unit are at a small hole in a wall of the duct through which the fluid flows (piezometer) or on the surface of a stationary tube at a point where the disturbances, created by inserting the tube, cancel. It is supposed that the thermodynamic properties of a moving fluid depend on static pressure in exactly the same manner as those of the same fluid at rest depend upon its uniform hydrostatic pressure.

Pressure, Total (TP): In the theory of the flow of fluids, the sum of the static pressure and the velocity pressure at the point of measurement. Also called dynamic pressure.

Pressure Drop: Pressure loss in fluid pressure, as from one end of a duct to the other, due to friction, dynamic losses, and changes in velocity pressure.

Primary Air: The initial air stream discharged by an air outlet (the air being supplied by a fan or supply duct) prior to any entrainment of the ambient air.

Primary Control: A device which directly or indirectly controls the control agent in response to needs indicated by the controller. Typically a motor, valve, relay, etc.

Properties, Thermodynamic: Basic qualities used in defining the condition of a substance, such as temperature, pressure, volume, enthalpy, entropy.

Proportional Band: The range of values of a proportional positioning controller through which the controlled variable must pass to move the final control element through its full operating range. Commonly used equivalents are "throttling range" and "modulating range."

Proportional Control: See Modulating Control. Psychrometer: An instrument for ascertaining the humidity or hygrometric state of the atmosphere.

Psychrometric Chart: A graphical representation of the thermodynamic properties of moist air.

Radiation, Thermal: The transmission of heat through space by wave motion; the passage of heat from one object to another without warming the space between.

Refrigerant: The fluid used for heat transfer in a refrigerating system, which absorbs heat at a low temperature and a low pressure of the fluid and rejects heat at a higher temperature and a higher pressure of the fluid, usually involving changes of state of the fluid.

Register: A grille equipped with an integral damper or control valve.

Relative Humidity (RH): The ratio of water vapor in the air as compared to the maximum amount of water vapor that may be contained.

Relay: An electromechanical switch that opens or closes contacts in response to some controlled action. Relay contacts *can* be normally open (N.O.) and/ or normally closed (N.C.). Relays may be electric, pneumatic, or a combination of both. PE and EP switches are relays.

Reset: A process of automatically adjusting the control point of a given controller to compensate for changes in outdoor temperature. The hot deck control point is normally reset upward as the outdoor temperature drops. The cold deck control point is normally reset downward as the outdoor temperature increases.

Resistance, Thermal: The reciprocal of thermal conductance.

Return Air: Air returned from conditioned or refrigerated space.

Saturation, Degree of: The ratio of the weight of water vapor associated with a pound of dry air to the weight of water vapor associated with a pound of dry air saturated at the same temperature.

Secondary Air: The air surrounding an outlet that is captured or entrained by the initial outlet discharge airstream (furnished by a supply duct or fan).

Sensible Heat: Sensible heat is any heat transfer that causes a change in temperature. Heating and cooling of air and water that may be measured with a thermometer is sensible heat. Heating or cooling coils that simply increase or decrease the air temperature without a change in moisture content are examples of sensible heat.

Sensible Heat Factor: The ratio of sensible heat to total heat.

Sensing Device: A device that keeps track of the measured condition and its fluctuations so that when sufficient variation occurs it will originate the signal to revise the operation of the system and offset the change. Example: a thermostat "bulb." A sensing device may be an integral part of a controller.

Sensor: A sensing element.

Set Point: The value of the controlled condition at which the instrument is set to operate. The set point in the example in "differential" might be $69^{1}12°$, the mid point of the differential.

Sorbent: See absorbent.

Specific Heat: Specific heat (C_p) is the amount of heat energy in Btu's required to raise the temperature of one pound of substance one degree Fahrenheit. The following are specific heat values at standard conditions:

water-C_p = 1.00 Btu/lb/^{o}F

air-C_p = 0.24 Btu/lb/^{o}F

Using these values in simple equations, gallons per minute or cubic feet per minute may be determined in a system if the Btu per hour and the temperature difference are known.

Specific Volume: The reciprocal of density and is used to determine the cubic feet of volume, if the pounds of weight are known. Both density and specific volume are affected by temperature and pressure. The specific volume of air under standard conditions is 13.33 cubic feet per pound and the specific volume of water at standard conditions is 0.016 cubic feet per pound.

Standard Air Density (d): Standard air density has been set at 0.075 Ib/cu. ft. This corresponds approximately to dry air at 70°F and 29.92 in. Hg. In metric units, the standard air density is 1.2041 kg/m^3 at 20°C and at 101.325 kPa.

Standard Conditions: The standard conditions referred to in environmental system work for air are: dry air at 70°F, and at an atmospheric pressure of 29.92 inches mercury (in.Hg.). For water, standard conditions are 68°F at the same barometric pressure. At these standard conditions, the density of air is 0.075 pounds per cubic feet and the density of water is 62.4 pounds per cubic foot.

Sublimation: A change of state directly from solid to gas without appearance of liquid.

Superheat, Specific: The difference between specific enthalpies of a pure condensable fluid between vapor at a given temperature above saturation and vapor at dry saturation, at the same pressure.

System Curve: A graphic presentation of the pressure vs. volume flow rate characteristics of a particular system.

Temperature, Dewpoint: The temperature at which the condensation of water vapor in a space begins for a given state of humidity and pressure as the temperature of the vapor is reduced. The temperature corresponding to saturation (100 percent relative humidity) for a given absolute humidity at constant pressure.

Temperature, Drybulb: The temperature of a gas or mixture of gases indicated by an accurate thermometer after correction for radiation.

Temperature, Effective: An arbitrary index which combines into a single value the effect of temperature, humidity, and air movement on the sensation of warmth or cold felt by the human body. The numerical value is that of the temperature of still, saturated air which would induce an identical sensation.

Temperature, Mean Radiant (MRT): The temperature of a uniform black enclosure in which a solid body or occupant would exchange the same amount of radiant heat as in the existing non-uniform environment.

Temperature, Saturation: The temperature at which no further moisture can be added to the air-water vapor mixture. Equals dew point temperature.

Temperature, Wet-Bulb: Thermodynamic wet bulb temperature is the temperature at which liquid or solid water, by evaporating into air, can bring the air to saturation adiabatically at the same temperature. Wet bulb temperature (without qualification) is the temperature indicated by a wet bulb psychorometer constructed and used according to specifications.

Temperature, Wet Bulb Depression: Difference between dry bulb and wet bulb temperatures.

Temperature Difference, Mean: Mean of difference between temperatures of a fluid receiving and a fluid yielding heat.

Thermodynamics, Laws of: Two laws upon which rest the classical theory of thermodynamics. These laws have been stated in many different, but equivalent ways.

The First Law: (1) When work is expanded in generating heat, the quantity of heat produced is proportional to the work expended; and, conversely, when heat is employed in the performance of work, the quantity of heat which disappears is proportional to the work done (Joule); (2) If a system is caused to change from an initial state to a final state by adiabatic means only, the work done is the same for all adiabatic paths connecting the two states (Zemansky); (3) In any power cycle or refrigeration cycle, the net heat absorbed by the working substance is exactly equal to the net work done.

The Second Law: (1) It is impossible for a self acting machine, unaided by any external agency, to convey heat from a body of lower temperature to one of higher temperature (Clausius); (2) It is impossible to derive mechanical work from heat taken from a body unless there is available a body of lower temperature into which the residue not so used may be discharged (Kelvin); (3) It is impossible to construct an engine that, operating in a cycle, will produce no effect other than the extraction of heat from a reservoir and the performance of an equivalent amount of work (Zemansky).

Transducer: The means by which the controller converts the signal from the sensing device into the means necessary to have the appropriate effect on the controlled device. For example, a change in air pressure in the pneumatic transmission piping.

Unitary System: A room unit which performs part or all of the air conditioning functions. It mayor may not be used with a central fan system.

Unloader: A device on or in a compressor for equalizing the high and low side pressures for a brief period during starting, in order to decrease the starting load on the motor; also a device for controlling compressor capacity by rendering one or more cylinders ineffective.

Valve, Modulating: A valve which can be positioned anywhere between fully on and fully off to proportion the rate of flow in response to a modulating controller (see modulating control).

Vapor, Water: Used commonly in air conditioning parlance to refer to steam in the atmosphere.

Ventilation: The process of supplying or removing air, by natural or mechanical means, to or from any space. Such air mayor may not have been conditioned.

Volume: Cubic feet per pound of dry air in the airwater vapor mixture as used in psychrometrics.

Volume, Specific: The volume of a substance per unit mass; the reciprocal of density.

Wet Bulb Temperature (WB): The temperature registered by a thermometer whose bulb is covered by a saturated wick and exposed to a current of rapidly moving air. The wet bulb temperature also represents the dew point temperature of the air, where the moisture of the air condenses on a cold surface.

Wet bulb Depression: Difference between dry bulb and wet bulb temperatures.

Zoning: The practice of dividing a building into small sections for heating and cooling control. Each section is selected so that one thermostat can be used to determine its requirements.

APPENDIX B
HVAC MASTERFORMAT$^{\text{TM}}$ SPECIFICATION OUTLINE

23 00 00 HEATING, VENTILATING, AND AIR CONDITIONING (HVAC)

23 01 00 Operation and Maintenance of HVAC Systems

- 23 01 10 Operation and Maintenance of Facility Fuel Systems
- 23 01 20 Operation and Maintenance of HVAC Piping and Pumps
- 23 01 30 Operation and Maintenance of HVAC Air Distribution
  - 23 01 30.51 HVAC Air Duct Cleaning
- 23 01 50 Operation and Maintenance of Central Heating Equipment
- 23 01 60 Operation and Maintenance of Central Cooling Equipment
  - 23 01 60.71 Refrigerant Recovery/Recycling
- 23 01 70 Operation and Maintenance of Central HVAC Equipment
- 23 01 80 Operation and Maintenance of Decentralized HVAC Equipment
- 23 01 90 Diagnostic Systems for HVAC

23 05 00 Common Work Results for HVAC

- 23 05 13 Common Motor Requirements for HVAC Equipment
- 23 05 16 Expansion Fittings and Loops for HVAC Piping
- 23 05 19 Meters and Gages for HVAC Piping
- 23 05 23 General-Duty Valves for HVAC Piping
- 23 05 29 Hangers and Supports for HVAC Piping and Equipment
- 23 05 33 Heat Tracing for HVAC Piping
- 23 05 48 Vibration and Seismic Controls for HVAC Piping and Equipment
- 23 05 53 Identification of HVAC Piping and Equipment
- 23 05 63 Anti-Microbial Ultraviolet Emitters for HVAC Ducts and Equipment
- 23 05 93 Testing, Adjusting, and Balancing for HVAC

23 06 00 Schedules for HVAC

- 23 06 10 Schedules for Facility Fuel Service Systems
- 23 06 20 Schedules for HVAC Piping and Pumps
  - 23 06 20.13 Hydronic Pump Schedule
- 23 06 30 Schedules for HVAC Air Distribution
  - 23 06 30.13 HVAC Fan Schedule
  - 23 06 30.16 Air Terminal Unit Schedule
  - 23 06 30.19 Air Outlet and Inlet Schedule
  - 23 06 30.23 HVAC Air Cleaning Device Schedule
- 23 06 50 Schedules for Central Heating Equipment
  - 23 06 50.13 Heating Boiler Schedule
- 23 06 60 Schedules for Central Cooling Equipment
  - 23 06 60.13 Refrigerant Condenser Schedule
  - 23 06 60.16 Packaged Water Chiller Schedule
- 23 06 70 Schedules for Central HVAC Equipment
  - 23 06 70.13 Indoor Central-Station Air-Handling Unit Schedule
  - 23 06 70.16 Packaged Outdoor HVAC Equipment Schedule

- 23 06 80 Schedules for Decentralized HVAC Equipment
    - 23 06 80.13 Decentralized Unitary HVAC Equipment Schedule
    - 23 06 80.16 Convection Heating and Cooling Unit Schedule
    - 23 06 80.19 Radiant Heating Unit Schedule

23 07 00 HVAC Insulation

- 23 07 13 Duct Insulation
- 23 07 16 HVAC Equipment Insulation
- 23 07 19 HVAC Piping Insulation

23 08 00 Commissioning of HVAC

23 09 00 Instrumentation and Control for HVAC

- 23 09 13 Instrumentation and Control Devices for HVAC
    - 23 09 13.13 Actuators and Operators
    - 23 09 13.23 Sensors and Transmitters
    - 23 09 13.33 Control Valves
    - 23 09 13.43 Control Dampers
- 23 09 23 Direct-Digital Control System for HVAC
- 23 09 33 Electric and Electronic Control Systems for HVAC
- 23 09 43 Pneumatic Control Systems for HVAC
- 23 09 53 Pneumatic and Electric Control Systems for HVAC
- 23 09 93 Sequence of Operations for HVAC Controls

23 10 00 FACILITY FUEL SYSTEMS

23 11 00 Facility Fuel Piping

- 23 11 13 Facility Fuel-Oil Piping
- 23 11 16 Facility Gasoline Piping
- 23 11 23 Facility Natural Gas Piping
- 23 11 26 Facility Liquefied-Petroleum Gas Piping

23 12 00 Facility Fuel Pumps

- 23 12 13 Facility Fuel-Oil Pumps
- 23 12 16 Facility Gasoline Dispensing Pumps

23 13 00 Facility Fuel-Storage Tanks

- 23 13 13 Facility Underground Fuel-Oil Storage Tanks
    - 23 13 13.13 Double-Wall Steel, Underground Fuel-Oil, Storage Tanks
    - 23 13 13.16 Composite, Steel, Underground Fuel-Oil Storage Tanks
    - 23 13 13.19 Jacketed, Steel, Underground Fuel-Oil, Storage Tanks
    - 23 13 13.23 Glass-Fiber-Reinforced-Plastic, Underground Fuel-Oil, Storage Tanks
    - 23 13 13.33 Fuel-Oil Storage Tank Pumps
- 23 13 23 Facility Aboveground Fuel-Oil, Storage Tanks
    - 23 13 23.13 Vertical, Steel, Aboveground Fuel-Oil, Storage Tanks
    - 23 13 23.16 Horizontal, Steel, Aboveground Fuel-Oil, Storage Tanks

  - 23 13 23.19 Containment-Dike, Steel, Aboveground Fuel-Oil, Storage Tanks
  - 23 13 23.23 Insulated, Steel, Aboveground Fuel-Oil, Storage Tanks
  - 23 13 23.26 Concrete-Vaulted, Steel, Aboveground Fuel-Oil, Storage Tanks

23 20 00 HVAC PIPING AND PUMPS

23 21 00 Hydronic Piping and Pumps

- 23 21 13 Hydronic Piping
  - 23 21 13.13 Underground Hydronic Piping
  - 23 21 13.23 Aboveground Hydronic Piping
  - 23 21 13.33 Ground-Loop Heat-Pump Piping
- 23 21 23 Hydronic Pumps
  - 23 21 23.13 In-Line Centrifugal Hydronic Pumps
  - 23 21 23.16 Base-Mounted Centrifugal Hydronic Pumps
  - 23 21 23.19 Vertical-Mounted, Double-Suction Centrifugal Hydronic Pumps
  - 23 21 23.23 Vertical-Turbine Hydronic Pumps
- 23 21 29 Automatic Condensate Pump Units

23 22 00 Steam and Condensate Piping and Pumps

- 23 22 13 Steam and Condensate Heating Piping
  - 23 22 13.13 Underground Steam and Condensate Heating Piping
  - 23 22 13.23 Aboveground Steam and Condensate Heating Piping
- 23 22 23 Steam Condensate Pumps
  - 23 22 23.13 Electric-Driven Steam Condensate Pumps
  - 23.22.23.23 Pressure-Powered Steam Condensate Pumps

23 23 00 Refrigerant Piping

- 23 23 13 Refrigerant Piping Valves
- 23 23 16 Refrigerant Piping Specialties
- 23 23 19 Refrigerant Safety Relief Valve Discharge Piping
- 23 23 23 Refrigerants

23 24 00 Internal-Combustion Engine Piping

- 23 24 13 Internal-Combustion Engine Remote-Radiator Coolant Piping
- 23 24 16 Internal-Combustion Engine Exhaust Piping

23 25 00 HVAC Water Treatment

- 23 25 13 Water Treatment for Closed-Loop Hydronic Systems
- 23 25 16 Water Treatment for Open Hydronic Systems
- 23 25 19 Water Treatment for Steam System Feedwater
- 23 25 23 Water Treatment for Humidification Steam System Feedwater

23 30 00 HVAC AIR DISTRIBUTION

23 31 00 HVAC Ducts and Casings

- 23 31 13 Metal Ducts

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APPENDIX C
SMACNA HVAC REFERENCES & RESOURCES

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APPENDIX D
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Photos 4-9 through 4-11 provided by Bell and Gossett-ITT (with permission)
Photo 4-12 and 4-13 provided by SPX Cooling Technologies, Inc. (with permission)

Photo 4-1
Centrifugal Chiller

McQuay International

Photo 4-2
Air Cooled Condenser

McQuay International

Photo 4-3
Condenser Coil
McQuay International

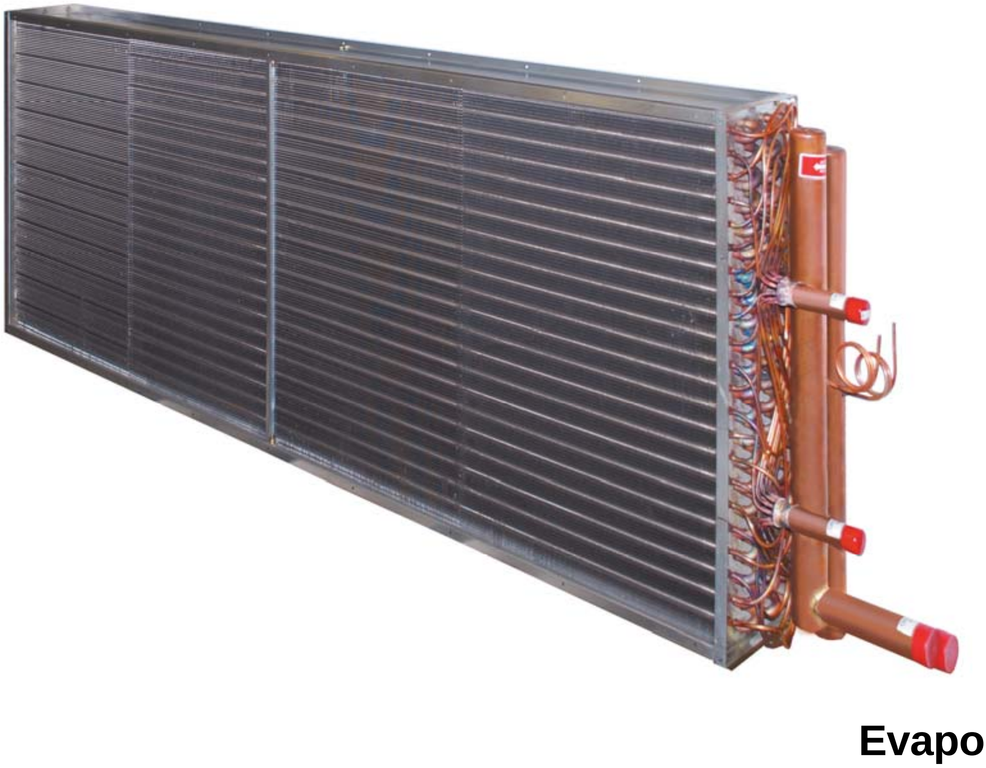

Photo 4-4
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Steam Coil
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Photo 4-6
Unit Ventilator
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Indoor Air Handling Unit

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Air Handling Unit – Panels Off

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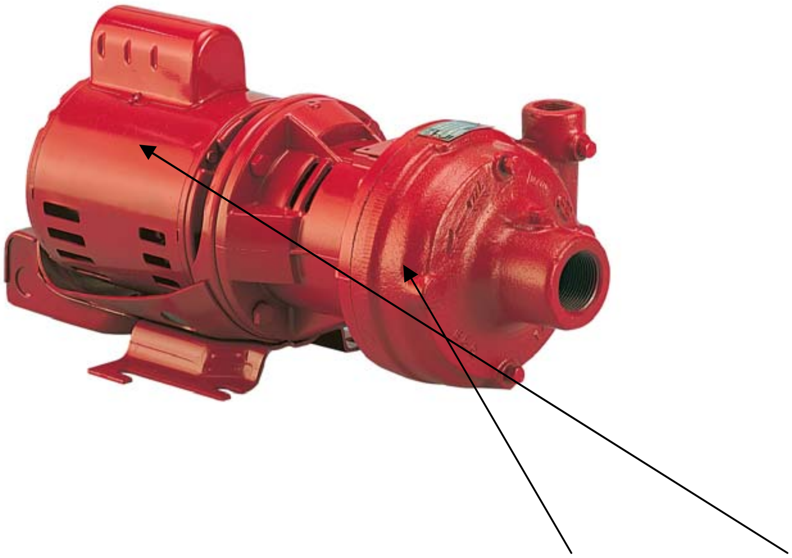
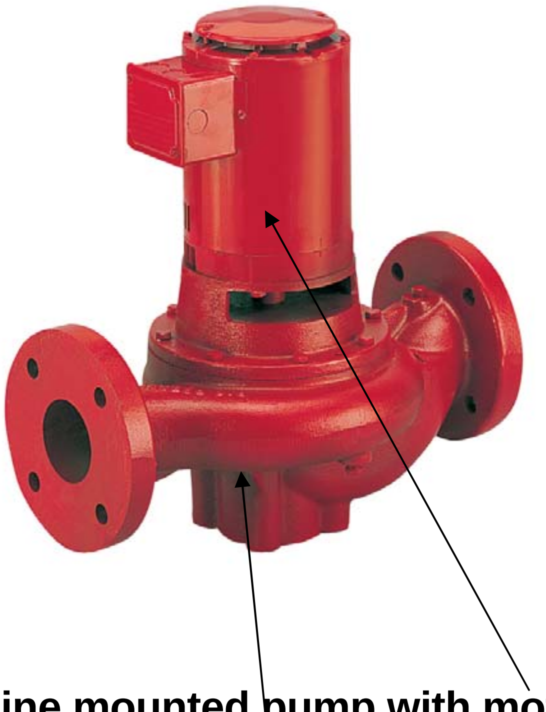


Foot-mounted, close-coupled pump with motor

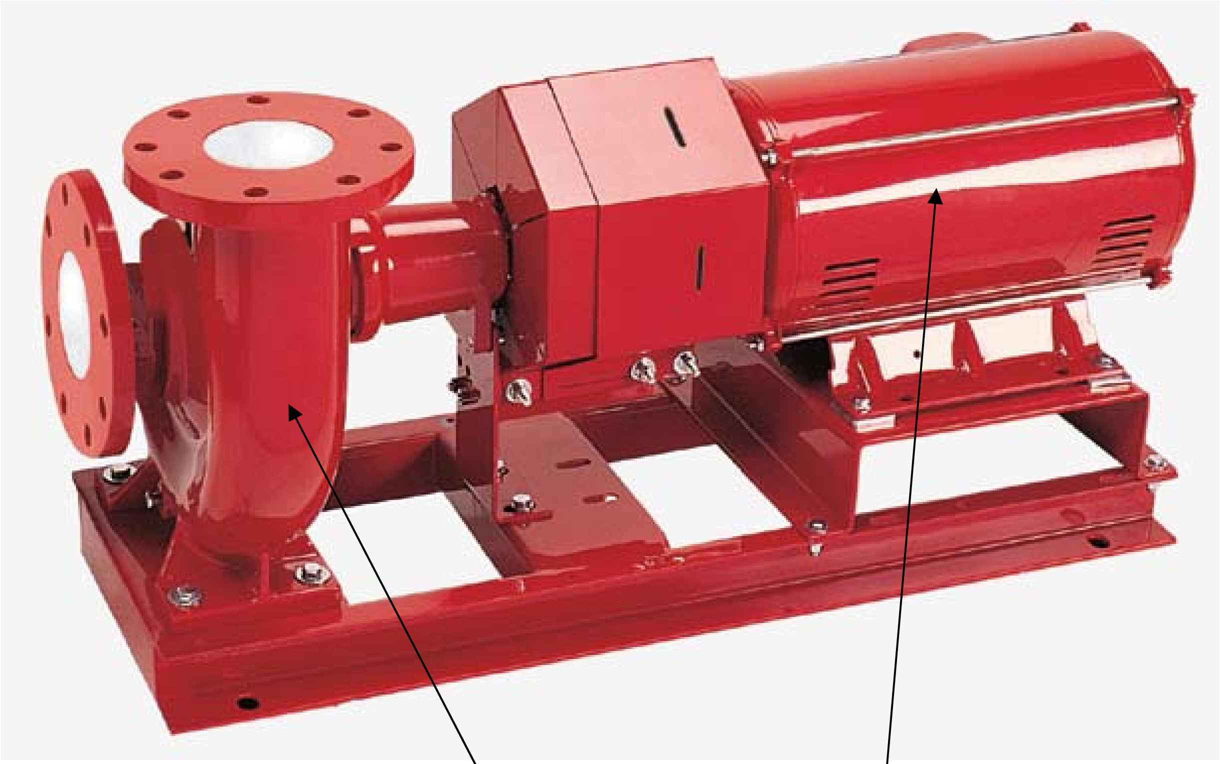
Bell and Gossett-ITT

Photo 4-10



Close-coupled in-line mounted pump with motor

Bell and Gossett-ITT



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Base-mounted, end-suction pump with motor
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Three Crossflow Open Circuit Cooling Towers with Axial Induced-Draft Fan

SPX Cooling Technologies, Inc.

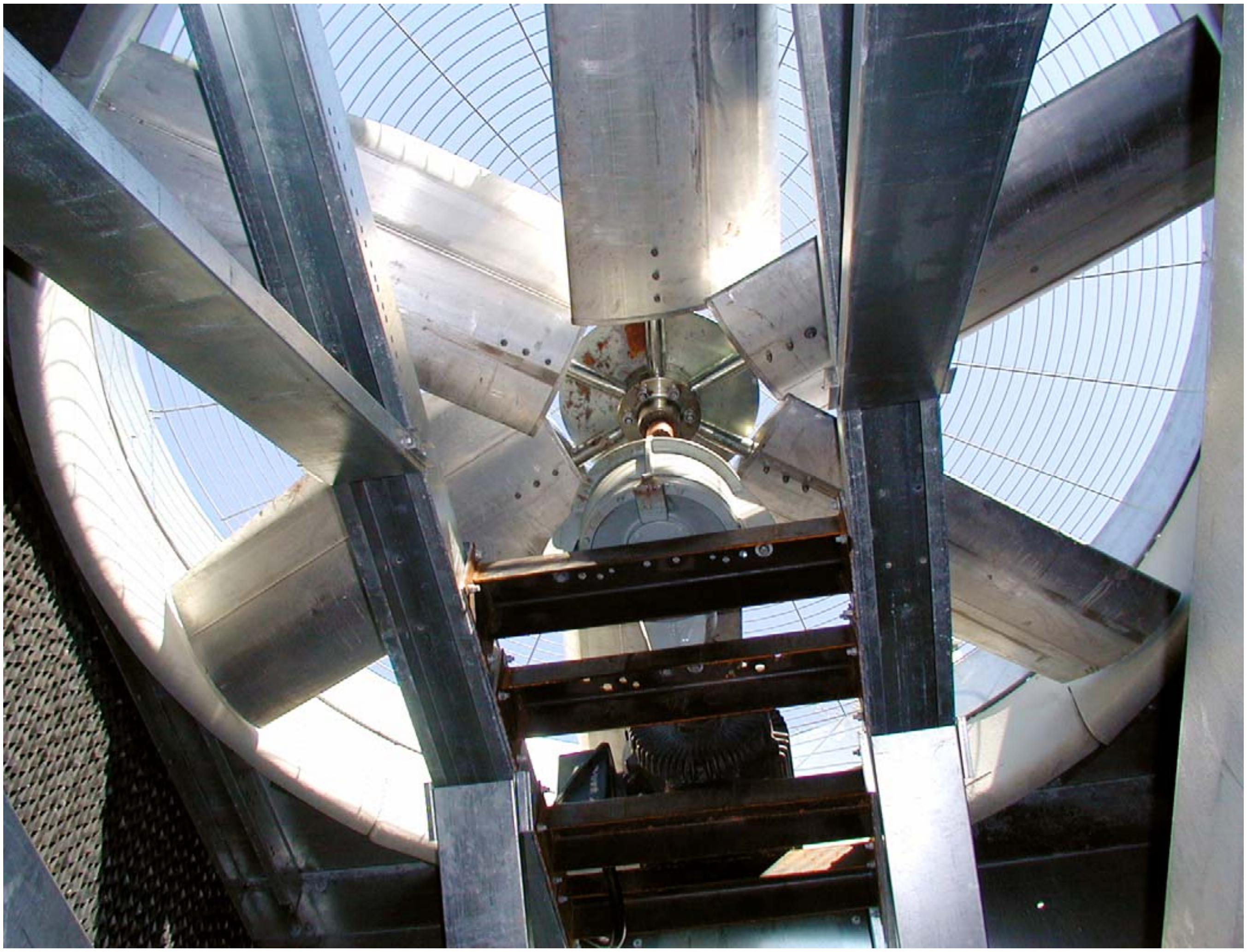

Photo 4-13
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