Chapter 6

Heating, Ventilating, and Air Conditioning

6.0 INTRODUCTION

The heating, ventilating, and air conditioning (HVAC) system for a facility is the system of motors, ducts, fans, controls, and heat exchange units which delivers heated or cooled air to various parts of the facility. The purpose of the HVAC system is to add or remove heat and moisture and remove undesirable air components from the facility in order to maintain the desired environmental conditions for people, products or equipment. Providing acceptable indoor air quality is a critical function of the HVAC system, and air movement to remove odors, dust, pollen, etc. is necessary for comfort and health. It may also be necessary to air-condition an area to protect products or to meet unusual requirements such as those in a laboratory or a clean room.

The HVAC system is responsible for a significant portion of the energy use and energy cost in most residential and commercial buildings. Because many industrial facilities do not have heated or cooled production areas, HVAC energy use does not account for as great a portion of the total energy use for these facilities. However, a number of manufacturing plants are fully heated and air conditioned, and almost all industrial facilities have office areas that are heated and cooled. Thus, looking for ways to save on the energy costs of operating a facility's HVAC system is an important part of any energy management program.

Many facilities have HVAC systems that were designed and installed during periods of low energy costs; these are often relatively expensive to operate because energy efficiency was not a consideration in the initial selection of the system. In addition, many HVAC systems are designed to meet extreme load conditions of very hot or very cold weather; they are then poorly matched to the average conditions that are experienced most of the time. Thus, improving the operation of the HVAC system provides many opportunities to save energy and reduce costs. In this chapter we describe how an HVAC system works, discuss the major components of HVAC systems, analyze heating and cooling loads and ventilation requirements, and give methods for improving the energy efficiency of existing HVAC systems.

6.1 HOW AN HVAC SYSTEM WORKS

Air in a facility absorbs heat from lights, people, industrial processes, and the sun, and air conditioning removes the excess heat in order to provide a comfortable working environment. The air conditioning system also removes excess humidity. In periods of cold weather, the heating system adds heat if the working environment is too cold for worker comfort. During the heating season, moisture may be added to increase the humidity. The HVAC system also provides ventilation and air movement even when no heating or cooling load is present.

HVAC systems vary depending on the fluid that is used as a heat exchange medium (usually water or air), on the particular requirements for the system, and on the type of system that was in style when the building was originally built. All heating systems have certain components in common: a source of heat, some means for transferring the heat from the point of generation to the point of use, and a control system. The source of heat is usually a boiler, a furnace, or the sun. For cooling systems, the source of cold temperature is usually a chiller, although cold air can be supplied either as the exhaust air from a cold area or as cool air brought into the facility during periods when the outside air is at a lower temperature than the inside air. The heat or cold is usually transferred from a furnace, a boiler, or a chiller to the air, and this air is distributed to the points of use.

An alternative system may distribute heated or chilled water to the points of use where the water heats or cools the air to be blown into the room. The control system may be as simple as a thermostat that turns on a furnace when it senses room temperature below a preset level, or it may be very elaborate, controlling air volume, humidity, and temperature through monitoring inputs from many sensors and actuating valves, motors, and dampers.

6.1.1 Dual-Duct System Operation

One way to understand how HVAC systems work is to first learn how one system works and then to see other systems as variations of that system. One of the more widely found HVAC systems is the dual-duct system, which is illustrated in Figure 6-1. Outside air is introduced through dampers (see Figure 6-1) which filter and control the amount of incoming air. This outside air is mixed with return air; the amount which

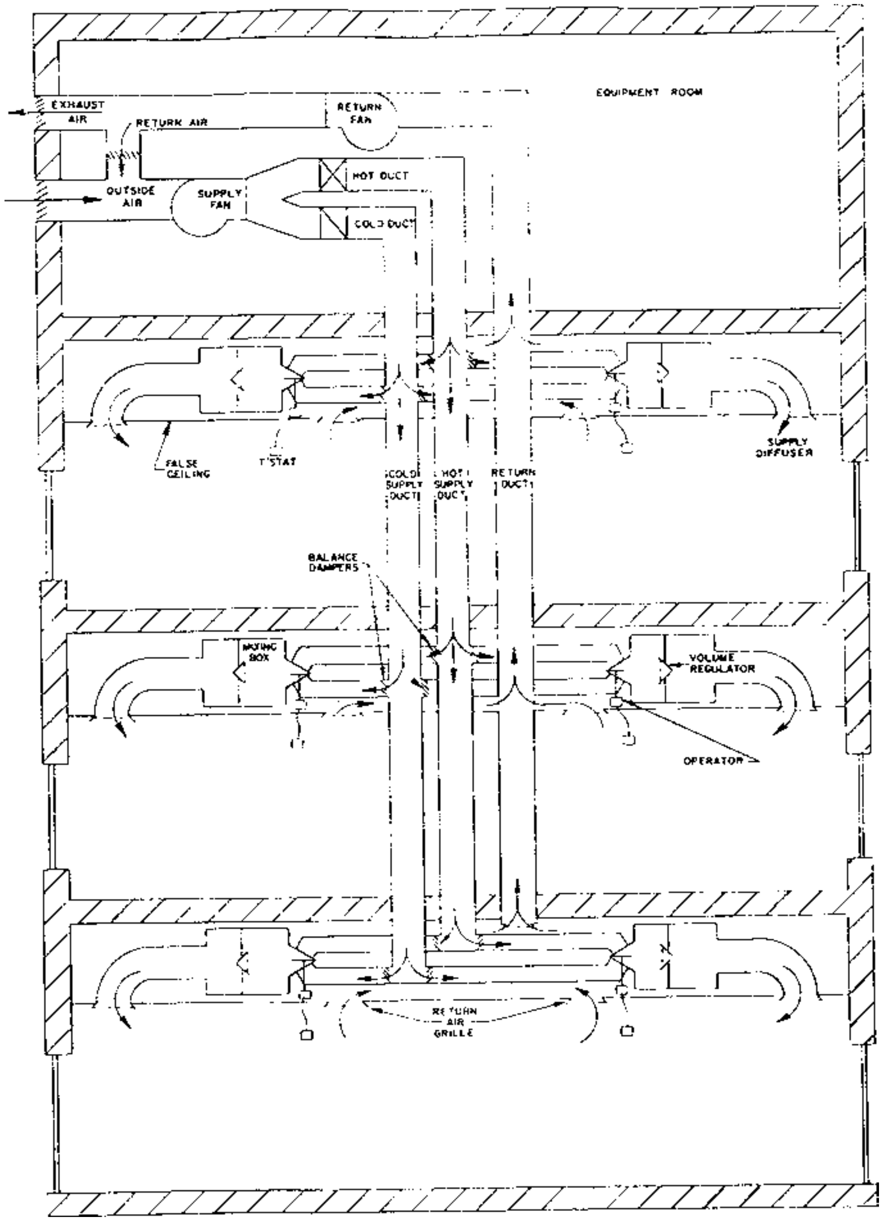

Figure 6-1 Dual-duct HVAC system.

is mixed is controlled by a return air damper. The air is then blown by a supply fan into both a hot duct and a cold duct. The air in the hot duct passes through heating coils and is sent at a preset temperature to the rooms where it is used. The air in the cool duct goes through conditioning coils and thence to the rooms; its temperature is set when it leaves the cooling coils. At each room, the cold and hot air go into a mixing box controlled by a thermostat; from the mixing box, the air with the desired temperature and moisture level enters the room. Later the air, with the heat, the cold, and the contaminants from the room, is removed through a return air grille and exhausted to the outside and/or returned as part of the intake air.

The dual-duct system has the advantage that it can accommodate widely differing demands for heating and cooling in different zones of a building by changing the ratio of hot to cold air in each zone. Its control system is also easily understood and relatively maintenance-free. The dual duct system has three main disadvantages. First, it requires much ductwork with attendant cost and space usage. Second, when the hot and cold ducts are next to each other, unproductive heat transfer takes place, and energy use and costs increase. Third, the use of energy to heat and cool simultaneously makes the dual-duct system a relatively inefficient system with respect to the energy required to perform the HVAC function.

Most of the original dual-duct systems in facilities have been modified so that the energy efficiency of the system is much better. Often this means that one of the ducts has been shut down so that heating and cooling are not provided at the same time for the entire system. This is an acceptable solution for some facilities with fairly uniform loads in all areas, and where moisture control is not a problem. Some of the systems have been modified to become variable air volume systems which are discussed in Section 6.1.4.1. Other systems use one duct for supplying heat or cooling to the core area of the facility, and perimeter fan-coil units are used to supply heat or cooling to the areas of the facility that are likely to need additional conditioned air.

6.1.2 Single-Duct, Terminal Reheat System Operation

A second type of system is a single-duct, terminal reheat system, and is illustrated in Figure 6-2. In this system, outside air enters through dampers, is mixed with return air in a mixing box or plenum, and is forced by a supply fan through a cooling unit. The air that has been cooled passes through a single supply duct to mixing boxes which contain a heating unit of some type—typically a hot water coil, and the air is then sent into a room. The return air system is similar to that described for the dual-duct system. When the source of heat for the reheat coil is a boiler, a common design fault is to have pumps continuously running water from the boiler

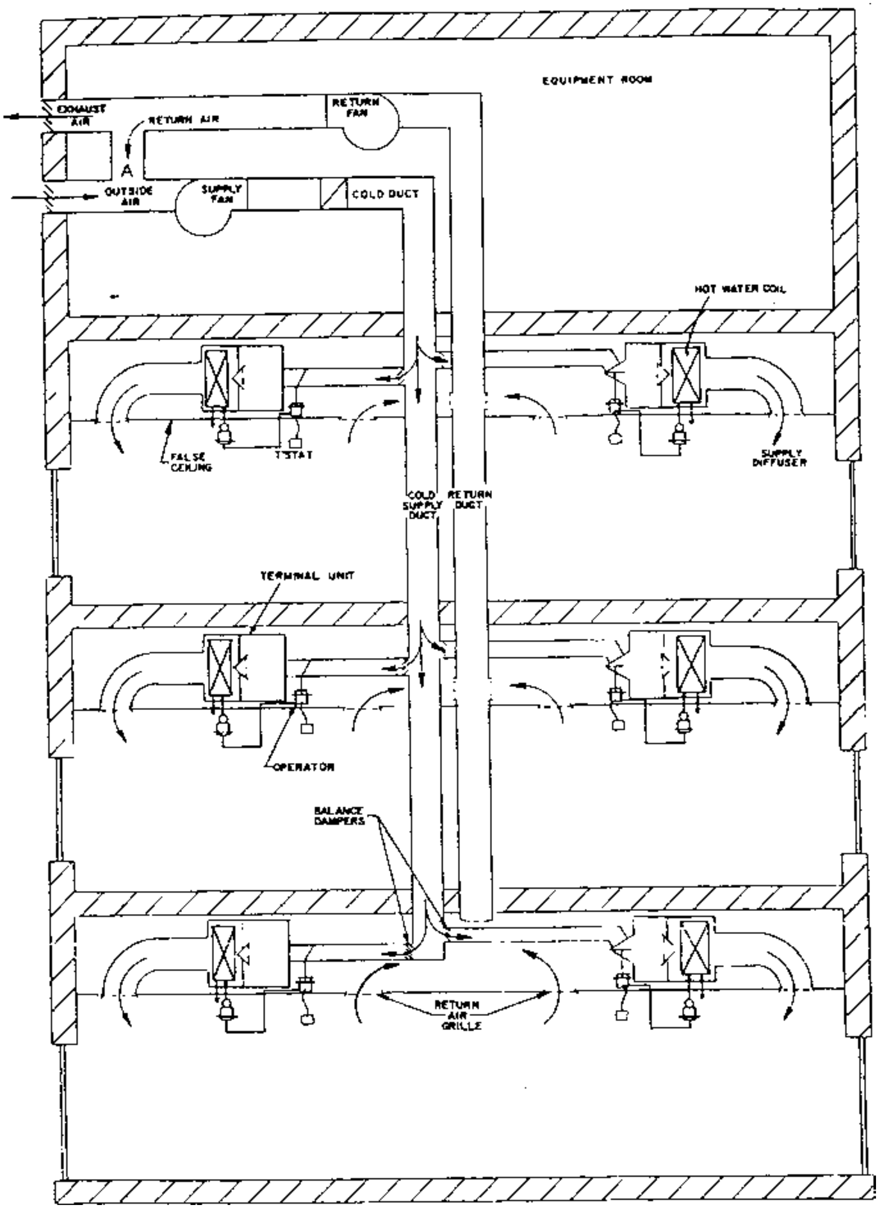

Figure 6-2 Terminal reheat HVAC system.

through the heating coil system. This uses electricity constantly for the pumps but avoids the thermal shock that might occur if cold water were injected into a warm boiler. A better alternative is to install a mixing valve at the boiler so that the pumps can be shut down when heating is not needed.

Many original terminal reheat systems used electric resistance heaters for the source of reheat. When electric energy costs greatly increased, most of these systems were modified to eliminate many of the terminal reheat units, and to use hot water coils and a gas or oil-fired boiler to supply the heat actually needed. Some of these terminal reheat systems were also modified to become variable air volume systems (see Section 6.1.4.1). Reheat systems are being used more now since ventilation standards have changed, and more outside air must now be brought into the facility.

6.1.3 System components

The typical components found in HVAC systems include dampers, grilles, filters, coils, fans, ductwork, and a control system. Each of these contributes to the operation of the HVAC system as follows:

Dampers. A damper controls a flow of air. If the damper is open, the air can flow unimpeded; if it is closed, the flow is reduced to 5-10% of open-damper flow, with the percentage dependent on the construction and maintenance of the damper. Dampers are usually used to regulate the flow of outside air into a system or to control the flow from one part of the system to another part, as in the case of a return air damper (A in Figure 6-2). In Figure 6-2, if the return air damper is closed and the outside air damper is open, all the heat (or cooling) in the return air is lost to the surrounding atmosphere. If the return air damper is open and the outside damper closed, then all the air is recirculated. Most HVAC systems operate somewhere between these two extremes, since some outside air must be supplied to buildings to meet health and safety code requirements.

Grilles. A screen—or grille—is usually placed upstream from a damper to catch bugs, lint, and debris before they go into the air distribution system. When a grille gets plugged or is blocked by objects such as furniture or stored material, this part of the air distribution system does not work. The authors saw a school where the temperature was consistently too hot for comfort although the air conditioning control system and other components seemed to be functioning properly. The grilles, however, were completely plugged with lint. When the grilles were cleaned, the problem disappeared.

Fans. Fans provide the power to move air through the air distribution system. A typical fan has three main parts: a motor, belts or a chain to transmit power from the motor to the fan blades (many small fans are direct drive), and the blades with their housing. If any one of these parts fails or is not connected properly, the fan will not move air, and this part of the air conditioning system will not work.

Heat Exchange Surfaces. The air that circulates through the HVAC system must usually be heated or cooled in order to be useful. This heating or cooling takes place when air is forced around a coil or finned surface containing hot or cold fluid. If these heat exchange surfaces are fouled with dirt, grease, or other materials with poor heat conduction properties, heat exchange will be inefficient, and more heat or cooling energy will have to be used in order to heat or cool air to the desired temperature.

Ductwork. Ductwork directs and conducts air from the heat exchange surfaces to the rooms where the hot or cold air is desired, and it conducts the exhaust air from these rooms back to the mixing plenum and to the outside. This function is impaired if the ducts leak or if loose insulation or other obstructions slow the airflow within the ducts.

Control System. An HVAC control system transforms the operating instructions for desired environmental conditions into the air temperatures and ventilation volumes desired in the working environment. The control system has the task of regulating the HVAC system so that these instructions are met as nearly as possible.

The control system accomplishes its function through a system of sensors, actuators, and communication links. The sensors send appropriate electrical or pneumatic signals when some temperature, pressure, or humidity threshold has been crossed. These signals are sent through a communication network, generally using either an electrical or pneumatic system. Signals can also be multiplexed through electrical supply lines, or radio transmission can be used. Upon reaching their destinations, the control signals are then translated into additional pneumatic or electrical signals that are used to open or close dampers, to regulate fans, and to initiate or stop the source of heating or cooling.

Dampers can be opened or closed to regulate the amount of incoming air, the amount of exhaust air that is mixed with fresh air, and the amount of air that is introduced into an area. Fans can be turned on or off to increase air coming into a room or being exhausted from it, or their speed can be regulated so that the amount of air coming into a room is no more than is needed for proper ventilation and temperature control. Boilers or chillers can be turned on to provide heat or cooling for the heat exchangers. Boiler controls are discussed in more detail in Chapter Eight.

6.1.4 Other HVAC System Types

Section 6.1.1 described the working of a dual-duct system, and Section 6.1.2 described the working of a terminal reheat system. Other common HVAC system types are variable air volume (VAV), fan coil, unit ventilator, induction, steam, and hot water systems. These systems are described briefly below because an energy auditor will invariably run into each of them at some time. For more detail, see References 6 and 7.

6.1.4.1 VAV systems.

In a variable air volume (VAV) system, tempered (heated or cooled) air is forced into a room at a rate dependent on the amount of heating or cooling desired. If the air volume needed is relatively constant, then a simple approach is to use dampers in VAV boxes installed in each duct opening where the air enters the room. If the air volume needed at different times changes significantly, the fan motor must have an adjustable speed drive so that the volume of air moved can be carefully controlled. If less heating or cooling is desired, less hot air is blown into the room. The advantage of this system is that only the amount of air needed is used, and, since power requirements vary as the cube of air volume moved, less air volume means less electrical consumption.

Some of the disadvantages of this system include the complexity and difficulty of maintaining the controls, and the need to use and control high-velocity airstreams. However, new control technologies have improved these problems, and this system is probably the most widely used HVAC system for installation in new buildings. Increased ventilation requirements for health and safety have resulted in more VAV systems needing fan motors with adjustable speed drives. Previously, VAV boxes in rooms could be shut down far enough to provide very low air flow rates; now this cannot be done, so the air flow must be more controllable to meet the required ventilation air flows. In addition, if moisture control is needed in a facility, it is necessary to have reheat to bring the temperature of the overcooled air back up to a comfortable temperature. Thus, even with the use of latest technology VAV systems it is still usually necessary to have reheat available.

6.1.4.2 Fan coil systems.

The fan coil system provides heat or cooling by using a fan to move room air across heating or cooling coils and back into the room. No outside air is introduced for ventilation, and no ductwork for outside air is needed. Air is usually distributed directly from the unit, and no ductwork is needed for supply air or return air. Control of the conditioned air is provided by varying the amount of heating or cooling fluid circulated through the coil and/or the fan speed.

6.1.4.3 Unit ventilators.

In this system, air is brought in directly from the outside and heated or cooled as it enters the room. A window air conditioner falls into this category as do many of the individual packaged room units in motels. The advantage of this system is that each room can be individually and easily controlled; the disadvantages are that installation costs are high and the occupants do not usually control temperatures so as to minimize energy consumption.

6.1.4.4 Induction units.

In these units, high-pressure supply air flows through nozzles and induces additional room air flow into the unit. This secondary air flows over heating or cooling coils and back into the room. This system provides both ventilation and heating or cooling at relatively low capital and energy costs. It also gives good local control of temperature. Its disadvantages are that its controls are complex and that each unit must be maintained regularly to keep it free of lint and dust.

6.1.4.5 Steam units.

In these systems, heat is produced from steam that condenses in radiators and is transferred either by fans or by natural convection. The condensate is then returned to the boiler where the steam was generated. The advantages of such systems include low initial and maintenance expenses for a multiroom installation. Disadvantages may include the need to operate the boiler when only a small part of the boiler design capacity is needed—for example, when only one or two rooms need heat and the boiler was designed to meet the needs of an entire building.

6.1.4.6 Water systems.

Water systems range from complex high-temperature units to the more familiar two-pipe units found in many old apartment buildings. In a typical water system, hot or cold water is pumped through coils and heats or cools air that is drawn around the coil by natural convection or by fans. In a two-pipe system, water enters the radiator through one pipe and leaves by another. In this system, complex valving is necessary to be able to change the system from heating to cooling, and the system operators must be skilled. In a four-pipe system, two pipes take and remove hot water and two take and remove chilled water, with the relative amounts of each depending on the amount of heating or cooling desired. The four-pipe system involves more plumbing than the two-pipe system but avoids the necessity for changing from hot to cold water throughout the system.

The main advantage of water systems is that they move a large amount of heating and cooling energy in return for a small amount of pumping energy; the amount of distribution energy per unit of heating or cooling is significantly less than that of an air system. The main disadvantage is the large amount of plumbing involved. Piping is expensive to buy and to install, and leaks in piping can cause far more expensive consequences than leaks in air-duct systems.

6.1.4.7 Heat pump systems.

A heat pump system is an HVAC system which uses the vapor-compression refrigeration cycle in a reverse mode. A heat pump system can move heat either to the inside or to the outside, so it can provide heating or cooling as the need arises. Single compressor systems up to about 25 to 30 tons are the most common. If a facility is going to be air conditioned, then the heat pump system is often a low cost system to provide the heating needed. In the moderate climate areas of the South and West, air-to-air heat pumps are very effective for heating. Use of water-to-air or ground-source heat pumps greatly expands the area where these systems are cost-effective.

6.2 PRODUCTION OF HOT AND COLD FLUIDS FOR HVAC SYSTEMS

6.2.1 Hot Fluids

Hot air, hot water and steam are produced using furnaces or boilers which are called primary conversion units. These furnaces and boilers can burn a fossil fuel such as natural gas, oil or coal, or use electricity to provide the primary heat which is then transferred into air or water. Direct production of hot air is accomplished by a furnace which takes the heat of combustion of fossil fuels or electric resistance heat, and transfers it to moving air. This hot air is then distributed by ductwork or by direct supply from the furnace to areas where it is needed.

Hot water is produced directly by a boiler which takes the heat from combustion of fossil fuels or electric resistance heat, and transfers it into moving water which is then distributed by pipes to areas where it is needed. A boiler might also be used to add more heat to the water to produce steam which is then distributed to its area of need. The combustion process and the operation of boilers and steam distribution systems are described in detail in Chapters Seven and Eight.

6.2.2 Cold Fluids

Cold air, cold water and other cold fluids such as glycol are produced by refrigeration units or by chillers, which are the primary conversion units. Refrigeration units or chillers commonly use either a vapor-compression cycle or an absorption cycle to provide the primary source of cooling which is then used to cool air, water or other fluids to be distributed to areas in which they are needed.

6.2.2.1 The basic vapor-compression cycle.

Room air conditioners and electrically powered central air conditioners with capacities up to 20-30 tons (or up to 100 tons with multiple compressors) operate using the basic vapor-compression cycle which is illustrated in Figure 6-3. There are four main components in a refrigeration unit using the vapor-compression cycle: the compressor, the condenser, the expansion valve and the evaporator. There is also a working fluid which provides a material that experiences a phase change from liquid to gas and back in order to move heat from one component of the system to another. The working fluid is typically a chlorofluorocarbon or CFC, but these CFCs are being phased out because of the damage they cause to the ozone layer. Hydrofluorocarbons or HFCs, or Hydrogen-

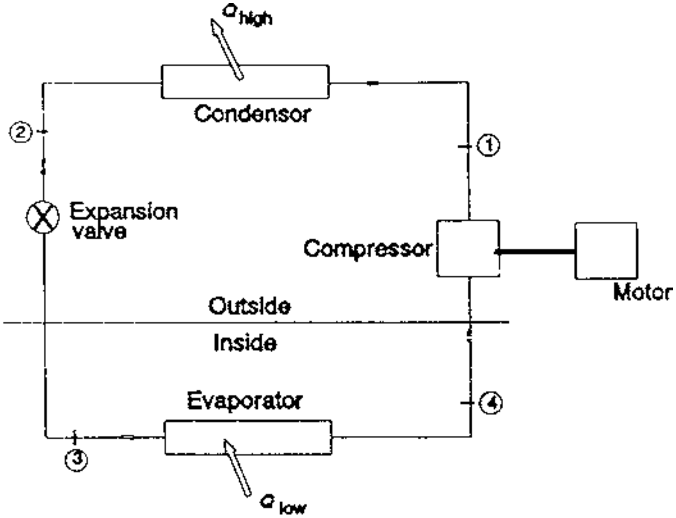

Figure 6-3. Vapor compression refrigeration cycle.

CFCs or HCFCs are already in use in some systems, and are expected to serve as replacements for CFCs until totally ozone-safe working fluids are developed. The replacement of CFCs is discussed in more detail in Section 6.2.3.

We can start the description of the vapor-compression cycle operation at any point in the diagram, so let's start at the compressor. As the working fluid enters the compressor, it is in the state of a low temperature and low pressure vapor. After compression, the fluid becomes a high pressure, superheated vapor. This vapor then travels to the condenser which is a heat transfer coil that has outside air blowing through it. As the heat from the vapor is transferred to the outside air, the vapor cools and condenses to a liquid. This liquid then travels to the expansion valve where both its pressure and temperature are reduced. Next, the low pressure, low temperature liquid travels to the evaporator, which is another heat transfer coil. Air from inside the conditioned space is blown through the evaporator coil, and heat from this air is absorbed by the working fluid as it continues to expand to a low pressure and low temperature vapor as it passes through the evaporator. The inside air has now been cooled as a result of some of its heat content being absorbed by the evaporator, and this cool air can be distributed to the area where it is needed. Finally, the cycle repeats as this low pressure and low temperature vapor from the evaporator returns to the compressor.

Rapid heat transfer from the inside air to the evaporator coil, and from the condenser to the outside air is critical to the proper operation and energy efficiency of a refrigeration unit using the vapor-compression cycle. These coils must be kept clean to allow rapid heat transfer. If the coils are dirty or air flow is partially blocked because of physical obstructions or shrubbery, the refrigeration unit will not work as effectively or as efficiently as it should. Duct leakage is also a common reason for poor cooling or low air flow. Proper operation also requires the correct amount of working fluid in the system. If leaks have allowed some of the fluid to escape, then the system should be recharged to its rated level.

6.2.2.2 Chillers.

A typical chiller provides cold water or some cold fluid such as glycol which is supplied to areas where secondary units such as fan-coil units are used to provide the cooling that is needed at each location. Chillers have capacities that vary widely, from a few hundred tons to several thousand tons. The majority of chillers use either the vapor-compression cycle or the absorption cycle as the basic cooling mechanism, and have secondary fluid loops that reject the unwanted heat to the outside air or water, and provide the cold fluid to the areas where it is needed. The schematic diagram illustrated in Figure 6-4 is typical of a water chiller that is water cooled.

In Figure 6-4 the condenser cooling water is usually supplied by a closed loop that goes to a cooling tower. The cooling tower is an evaporative cooler that transfers the heat from the water to the outside air through the process of evaporation as the water is sprayed or falls through the air. If lake water or ground water were used in an open loop, the water would simply be supplied from one location and returned to a different location in the lake or in the ground.

The chilled water produced by the evaporator is circulated in another secondary closed loop to the parts of the facility where it will be used to provide air conditioning or process cooling. Individual fan coil units can be used in rooms, or centralized air handling units can be used to take a larger quantity of cooled air and distribute it to various parts of the facility. Part of the chilled water may be used to circulate through production machines such as plastic injection molding machines, welders, or metal treatment baths. Chilled water or other chilled fluids may be used to provide refrigeration or freezing capability for various types of food processing, such as meat packing or orange juice processing.

There are three types of mechanical compressors used in chillers. Small compressors used in chillers with capacities up to about 50 tons are almost always reciprocating compressors; they may also be used in chill-

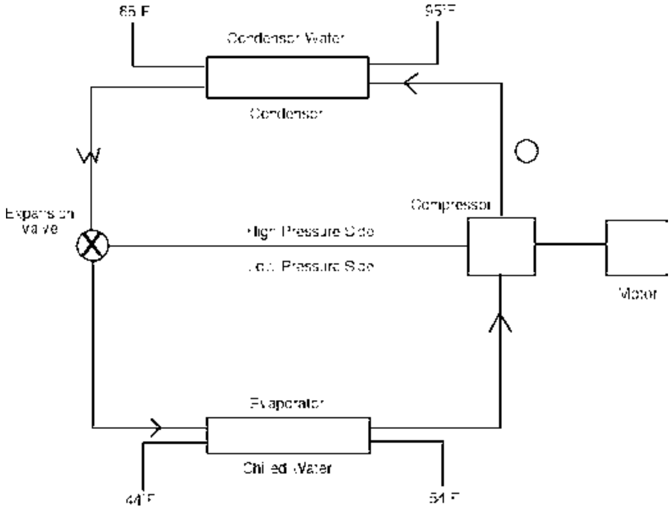

Figure 6-4. Diagram of a typical chiller.

ers up to around 250 tons. Rotary screw compressors are used in chillers as small as 40-50 tons, and in large units up to and somewhat over 1000 tons. Centrifugal compressors are used in chillers as small as 75 tons, and in very large units up to and over 5000 tons.

6.2.3 Replacement of CFCs with alternative working fluids

Releases of many working fluids or refrigerants commonly used in HVAC systems can cause damage to the ozone layer in the earth's stratosphere [9]. The refrigerants degrade to release chlorine molecules which then proceed to break down ozone. Ozone, a molecule containing three oxygen atoms, is effective in filtering out ultra-violet (UV) radiation. The hole in the ozone layer over the Antarctic has allowed a large increase in the amount of UV radiation reaching the earth's surface. Sheep in southern Argentina received sunburns for the first time in recorded history when the ozone hole drifted northward. More importantly, the increase in UV radiation may damage marine crustaceans which form a vital link near the bottom of the food chain in the world's oceans.

The production of chlorinated fluorocarbons (CFC) used in refrigeration and air-conditioning systems will cease on January 1, 1996. Several of the most common refrigerants in use (i.e., R-11 and R-12) will no longer be manufactured. They will be available from recyclers for a short period of time but probably at high cost. Several alternative refrigerants under development may be suitable substitutes.

There are problems associated with most of the alternatives in many applications. The energy efficiency and capacity of the systems may be less than that of systems using CFC's. This will require more energy use and its associated pollution and production of greenhouse gases. Other problems include: incompatibility with commonly used lubricants and gasket materials, toxicity, and difficulty in retrofitting existing systems (e.g., replacement of sensors, motors, impellers, gears, etc.).

The current frontrunners in the field of substitutes are R-123 and R-245ca for R-11 and R-134a for R-12. Another short-term remedy is to use halogenated chlorofluorocarbons (HCFC) such as the commonly used R-22 or a mixture of R-22 with other compounds (i.e., near azeotropic compounds). HCFC compounds have less ozone depletion potential (ODP) than CFC compounds (i.e., ODP of R-11 is 1.0 by definition). For example, R-22 has an ODP of 0.05. HCFC production is slated to be phased out around 2030, but there is pressure to accelerate the timetable.

Large industrial refrigeration needs can be met with existing compounds such as ammonia or water/lithium bromide. These are well-developed technologies which predate the common use of CFC compounds for refrigeration.

Many facilities will replace their existing equipment with new systems containing refrigerants with low ODP and then recover the existing refrigerants for use in their other equipment.

6.3 ENERGY EFFICIENCY RATINGS FOR HVAC SYSTEM COMPONENTS

6.3.1 Boilers and furnaces

The efficiency of furnaces and boilers is specified in terms of the ratio of the output energy supplied to the input energy provided. This efficiency is shown in equation 6-1 below:

$$\text{Efficiency (\%)} = [\text{heat output}/\text{heat input}] \times 100 \qquad (6\text{-}1)$$

Efficiency specifications differ depending on where the heat output is measured. Combustion efficiency will be the highest efficiency number since it measures heat output at the furnace or boiler. Combustion efficiency can be measured with a stack gas analyzer, or it can be measured by determining the temperature and flow rate of the air or water from the furnace or boiler, and then calculating the heat output.

Furnace efficiencies can range from 65% to 85% for most standard furnaces, and up to 98% for pulse-combustion, condensing furnaces. Boiler efficiencies range from about 65% for older, smaller boilers to 85% for newer, larger models. Furnace and boiler efficiencies should be checked periodically, and tuned up to keep the efficiencies at their upper levels and reduce energy costs.

6.3.2 Air conditioners

The efficiencies of air conditioners are usually measured in terms of their Energy Efficiency Ratios or EERs, or their Seasonal Energy Efficiency Ratios or SEERs. In either case, the efficiency is specified as:

$$\text{EER} = \text{Btu of cooling}/(\text{watt-hours of electric energy input}) \qquad (6\text{-}2)$$

The EER value is measured at a single temperature for the outside air, while the SEER involves a weighted average of the EERs over a typical season with a range of outside temperatures. SEERs usually range from 0.5 to 1.0 units higher than the corresponding EERs. Air conditioning units with capacities of five tons or less are rated with SEERs, while units over five tons are rated with EERs. Current levels of SEERs for air conditioners can reach 15 or greater, but most units have SEERs around 10. Federal appliance efficiency standards and ASHRAE standards have increased in the last few years, and will increase further with standards set in the 1992 National Energy Policy Act [10].

Example 6-1: A five ton air conditioner has an average electric load of 8 kW. What is its SEER?

Solution: Using Equation 6-2 gives:

$$\begin{aligned}\text{SEER} &= (5\text{ tons})\,(12{,}000\text{ Btu/hr/ton})/(8\text{ kW})(1000\text{ W/kW})\\ &= 60{,}000\text{ Btu}/8{,}000\text{ Wh}\\ &= \underline{7.5\text{ Btu/Wh}}\end{aligned}$$

6.3.3 Chillers

Chiller efficiency is usually measured in terms of a Coefficient of Performance (COP) which is expressed as:

$$\text{COP} = \text{heat absorbed by the evaporator}/[(\text{heat rejected by the condenser}) - (\text{heat absorbed by the evaporator})] \qquad (6\text{-}3)$$

Chiller efficiencies depend on what type of compressor is used in the chiller, and whether air or water cooling is used. COPs may be as low as 2.5 for small chillers, and up to 7.0 for large, water-cooled, centrifugal or screw compressor chillers. Absorption chillers have COPs that range from 0.4 to 1.2.

Chiller efficiencies may also be expressed as EERs, where

$$\text{EER} = \text{COP} \times 3.412\text{ Btu/Wh} \qquad (6\text{-}4)$$

Example 6-2: A 100-ton chiller has a COP of 3.5. What is its electrical load?

Solution: Using Equation 6-2 and rearranging it gives:

$$\begin{aligned}\text{electrical load} &= \text{cooling capacity/EER}\\ &= (100\text{ tons})(12{,}000\text{ Btu/hr/ton})/(3.5)(3412\text{ Btu/kWh})\\ &= \underline{100.5\text{ kW}}\end{aligned}$$

Chiller efficiencies are greatly affected by the amount of load on the system. Part-load COPs are as much as one-fourth or one-fifth of the full-load COPs. Typically, a chiller must operate at 70% or greater load to be close to its full-load COP.

6.4 HEATING, COOLING, AND VENTILATING LOADS

One of the easier ways to reduce costs in HVAC systems is to reduce the amount of energy that must be added to or extracted from an area to bring the area to the desired temperature range. Two major strategies for accomplishing this are available: (1) reduce the heating or cooling load; (2) change the targeted temperature range. The amount of *cooling* needed in an area can be reduced by reducing the amount of heat brought into the area through the walls, by reducing the number of people present, by reducing the number of heat sources such as lighting, or by modifying the energy consumption characteristics of the industrial processes. The amount of *heating* needed can be reduced by increasing the amount of machinery located indoors, by capturing some of the heat from lights, by reducing infiltration of cold outside air, or by insulating roofs or ceilings so that less heat escapes. In any of these examples, the cooling or heating load is being changed.

The second strategy is to change the temperature range that is considered to be desirable. This means changing the temperature limit above which air cooling occurs—the upper set point, and the temperature limit below which heating occurs—the lower set point. If heating does not start until the temperature is 55°F or lower, less heat will be used than if the threshold temperature for heating is 65°F. Similarly, an upper control limit of 85°F is more economical than a limit of 75°F. Changing these temperatures has the effect of changing the heating or cooling load imposed upon the HVAC system, although none of the heat sources are changed.

6.4.1 Heating and Cooling Load Calculations

The heating and cooling loads in a building occur because of (1) heat given off by people; (2) radiant energy from the sun that enters through windows, is absorbed by furniture, walls, and equipment, within the building, and is later radiated as heat within the building; (3) heat conducted through the building envelope (walls, roofs, floors, and windows) to or from the environment around the building; (4) waste heat given off by processes and machinery within the building; (5) heat given off by lighting; and (6) heat or cooling lost to ventilation or infiltration air. In this section we emphasize managing the energy costs of an existing building by examining those aspects of the heating and cooling load that can be changed by moderate or low expense or by scheduling. Reference 1 can be used for design purposes because it contains a sufficiently detailed methodology for calculating these heat and cooling losses and their interactions.

6.4.1.1 Heating and cooling load: people.

People give off heat, and the amount they give off depends on the type of work they are doing, the temperature of their surroundings, and whether they are men or women. Table 6-1 gives representative values for the heat given off under various conditions. If no cooling or heating takes place during nonworking hours, the figures in Table 6-1 can be used directly. If cooling or heating takes place when the work force is not present, the later reradiation of heat given off by people and absorbed by equipment and surroundings must be taken into account as described in the ASHRAE Fundamentals Handbook [1].

Table 6-1. Rates of Heat Gain from People

Activity	Total heat gain for male adults (Btu/h)
Seated at rest	400
Seated, writing	480
Seated, typing	640
Standing, light work or slow walking	800
Light bench work	880
Normal walking, light machine work	1040
Heavy work, heavy machine work, lifting	1600

Note: Heat gain from adult females is assumed to be 85% of that for adult males.
Source: From *1993 Fundamentals Handbook*, ©1993. Reprinted with permission from the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Ga.

People-generated heat can be managed in several ways. The first management technique is that of scheduling: decreasing the number of people in an air-conditioned area during the time of peak energy consumption will decrease the amount of heat that must be removed and thus will decrease this component of the peak demand. If the work of people can be scheduled when the outside temperature is lower than the inside temperature, it is often possible to remove people-generated heat by introducing colder outside air rather than by using mechanical refrigeration. Another technique is to remove people. This is accomplished by replacing people by automated equipment such as automated storage and retrieval systems. Removing the people decreases the cooling load and may completely eliminate the necessity for cooling (or heating) an area.

6.4.1.2 Heating and cooling load: solar radiation.

The cooling load due to solar radiation through windows can be calculated by

$$q = \Sigma\,(A \times SC \times MSHG \times CLF) \tag{6-5}$$

where q = cooling load (Btu/hr)
A = window area (square feet)
SC = shading coefficient
MSHG = maximum solar heat gain (Btu/hr/ft^2)
CLF = cooling load factor

The total cooling load is found by summing the cooling loads for all surfaces of the building envelope. In Equation 6-5, the window area A must be measured. The shading coefficient SC depends on the kind of glass, the indoor shading (roller blinds or venetian blinds), and the average outside wind velocity. For single-pane glass, typical values range from 0.53 for 1/2-inch heat-absorbing glass to 1.00 for 1/8-inch clear glass; a white roller shade inside a clear 3/8-inch glass pane gives a shading coefficient of 0.25. Additional values of the shading coefficient can be obtained from glass vendors and from Reference 1. Changing glass types and installing shades are energy management measures that can make a significant change in the shading coefficient. Adding sun screens can reduce the shading coefficient to about 0.2, and using reflective film on windows can provide a shading coefficient of around 0.4.

The maximum solar heat gain and the cooling load factors, however, are fixed by the location and design of the structure. The maximum solar heat gain (MSHG) depends on the month, the hour, the latitude, and the direction the surface is facing. For 40° north latitude (Denver and Salt Lake City), these factors are shown in Table 6-2. The cooling load factor (CLF) measures the fraction of energy absorbed at a given time that is radiated as heat at a later time. This factor, like the shading coefficient, depends on the interior shading. Representative values for this factor are given in Table 6-3 for a building with medium-weight construction (approximately 70 lb of building material per square foot of floor area). Additional values for these factors can be found in Reference 1.

Table 6-2. Maximum Solar Heat Gain Factors
(Btu/h•ft^2 for 40° North Latitude)

	Surface orientation					
	N	NE/NW	E/W	SE/SW	S	Horizontal
Jan.	20	20	154	241	254	133
Feb.	24	50	186	246	241	180
March	29	93	218	236	206	223
April	34	140	224	203	154	252
May	37	165	220	175	113	265
June	48	172	216	161	95	267
July	38	163	216	170	109	262
Aug.	35	135	216	196	149	247
Sept.	30	87	203	226	200	215
Oct.	25	49	180	238	234	177
Nov.	20	20	151	237	250	132
Dec.	18	18	135	232	253	113

Source: From Reference 1. Reprinted with permission from the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Ga.

Equation 6-5 shows what factors can be altered to manage the solar component of the cooling load. For buildings in a hot climate, it is often cost effective to cover all outside windows and thus reduce the area A through which solar radiation enters the building. If, however, heating is more of an expense than cooling, it may be possible to increase the area and use passive solar heating.* The shading coefficient (SC) can be changed by installing shades, heat-absorbing glass, or reflective coatings. The maximum solar heat gain (MSHG) can be used to help decide where to locate people and equipment within a building relative to the location of windows. More heat will come in if the windows are facing south than

---

*For more detail on the possibilities of this approach, see Reference 2.

Table 6-3. Cooling Load Factors for Glass

Solar time	Direction window is facing								
	N	NE	E	SE	S	SW	W	NW	Hor.
Without Interior Shading									
2 a.m.	.20	.06	.06	.08	.11	.13	.13	.12	.14
4	.16	.05	.05	.06	.08	.10	.10	.09	.11
6	.34	.21	.18	.14	.08	.09	.09	.09	.11
8	.46	.44	.44	.38	.14	.12	.10	.11	.24
10	.59	.40	.51	.54	.31	.15	.12	.14	.43
12	.70	.33	.39	.51	.52	.23	.14	.17	.59
2 p.m.	.75	.30	.32	.40	.58	.44	.29	.21	.67
4	.74	.26	.26	.33	.47	.58	.50	.42	.62
6	.79	.21	.21	.25	.36	.53	.55	.53	.47
8	.50	.15	.15	.18	.25	.33	.33	.32	.32
10	.36	.11	.11	.14	.18	.24	.23	.22	.24
12	.27	.08	.08	.10	.14	.18	.17	.16	.18
With Interior Shading									
2 a.m.	.07	.02	.02	.03	.04	.05	.05	.04	.05
4	.06	.02	.02	.02	.03	.04	.04	.03	.04
6	.73	.56	.47	.30	.09	.07	.06	.07	.12
8	.65	.74	.80	.74	.22	.14	.11	.14	.44
10	.80	.37	.62	.79	.58	.19	.15	.19	.72
12	.89	.27	.27	.49	.83	.38	.17	.21	.85
2 p.m	.86	.24	.22	.28	.68	.75	.53	.30	.81
4	.75	.20	.17	.22	.35	.81	.82	.73	.58
6	.91	.12	.11	.13	.19	.45	.61	.69	.25
8	.18	.05	.05	.07	.09	.12	.12	.12	.12
10	.13	.04	.04	.05	.07	.08	.08	.08	.08
12	.09	.03	.03	.04	.05	.06	.06	.06	.06

Note: Solar time = local standard time (LST) + 4 min × (LST meridian – local longitude) + correction for the month (from – 13.9 min in February to + 15.4 min in October).

Source: From Reference 1. Reprinted with permission from the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Ga.

if the windows are facing north. If a close visual contact with the outside is desired but the sun heat is not, both conditions can be met with windows facing the north. The cooling load factor is reduced by shading, since less heat is absorbed by furniture and walls to be reradiated later.

6.4.1.3 Heating and cooling load: conduction

In addition to inside heating caused by radiation of solar energy absorbed by inside materials, the sun heat combines with the outside temperatures to create heating due to conduction through the walls and the roof. Although writing and solving the heat conduction equations are beyond the scope of this text, several observations can be made that are relevant to energy management. First, the amount of heat gain or loss through a wall depends on the thermal conductivity—or U value—of the wall. Adding insulation to walls or roofs can significantly reduce the unwanted heat gain or heat loss through a wall and can be very cost effective if the main component of the cooling load is from conduction rather than from inside sources. Thermal conductivity, insulation, and the calculation of heat transfer through walls and roofs are discussed in detail in Chapter 11.

Second, the construction of the wall and roof is also an important factor, with the material used to build the structure having a potential thermal storage effect that can be utilized. The so-called *flywheel effect* describes this: In the same way that a flywheel at motion tends to remain in motion, a warm wall tends to remain warm and to radiate heat after the sun is down. The amount of heat and the time the wall continues to radiate depend on the construction of the wall in the same sense that the speed and running time of a released flywheel depend on the construction of the wheel. If an existing building has massive walls, it may be possible to schedule work hours so as to take advantage of the flywheel effect and obtain free heating or cooling. These points are discussed in Reference 3.

Heating or cooling loads due to conduction through a wall can be approximated using Heating Degree Day (HDD) or Cooling Degree Day (CDD) data. Definitions of HDDs and CDDs and calculation methods were given in Section 2.1.1.4. The method involves the use of the heat flow equation 11-9 given in Chapter 11. In this equation, A is the area of the wall, U is the thermal conductivity of the wall, Q is the heat flow through the wall, and the temperature difference ΔT is replaced by the number of heating or cooling degree days, HDD or CDD.

$$Q = U \times A \times (\mathrm{DD}/\mathrm{year}) \times 24\ \mathrm{h}/\mathrm{day} \tag{6-6}$$

Example 6-3: A wall has an area of 100 ft^2 and has a thermal conductivity of 0.25 Btu/ft^2•h•°F. If there are 3000 degree days in the heating season, what is the total amount of heat lost through the wall?

Solution: The heat lost through the wall is found using equation 6-6 as:

$$\begin{aligned} Q &= (0.25\ \text{Btu/ft}^2\bullet\text{h}\bullet{}^\circ\text{F}) \times 100\ \text{ft}^2 \times (3000\ {}^\circ\text{F days/year}) \\ &\qquad \times 24\ \text{h/day} \\ &= \underline{1{,}800{,}000\ \text{Btu/year}} \end{aligned}$$

The degree day method has many potential problems that limit its value in finding the total heating needs of a building or facility. First, it only provides an approximate value for the heat flow due to conduction. It does not take into account the moisture in the air; internal heat loads that might provide less than or greater than a 5°F inside temperature gain; solar heat gain; or many other factors.

6.4.1.4 Heating and cooling load: equipment.

The fourth major source of heating is from equipment. The energy consumption in Btu per hour from ovens, industrial processes such as solder pots that use much heat, and many other types of equipment can either be read directly from nameplates or can be approximated from gas or electricity usage by assuming that every kWh of electricity contributes 3412 Btu of heat at the point of use and that each Mcf (thousand cubic feet) of gas has an energy content of 1 million Btu.

The efficiency for a single-phase motor is usually 50-60%, and the efficiency for a three-phase motor is usually 60-95%. The energy used by other kinds of equipment can be found in Reference 1, from equipment vendors, and from gas and electric utilities. Decreasing or rescheduling the amount of equipment using electricity or gas at a given time has a twofold effect. First, the actual energy used at that time is decreased. Second, the heat introduced into the space is also reduced. If this heat must be removed by cooling, the cooling load is thus reduced by turning off this equipment. If this heat is desirable, Equations 6-9, 6-10 and 6-11 can be used to indicate how much waste heat can be made available by scheduling or reducing the number of electric motors.

The amount of heat given off by a motor can also be determined from its nameplate rating in kW if there is one, or it can be estimated from the nameplate voltage and current used by the motor. If it is a single-phase motor, the energy consumed per hour by the motor is given by

$$\text{kWh/h} = \text{kW} \times \text{use factor (fraction of time that the motor is in use)} \qquad (6\text{-}7)$$

or by the calculation involving the voltage, current and power factor

$$\text{kWh/h} = \text{voltage} \times \text{current} \times \text{power factor} \times \text{use factor} \qquad (6\text{-}8)$$

The amount of heat that is given off in the space being analyzed depends on the job the motor is doing. In most cases, all of the energy used by the motor shows up as heat added to the space. This may seem odd at first, but when the physical factors are considered, the result is quite clear. First, the motor is not 100% efficient, so some of the motor energy is lost directly to heat through losses in the armature and field windings, losses in the motor core and friction losses in bearings. This heat makes the motor feel hot to the touch, and directly heats up the space.

The remaining motor energy is then used for some application. However, in most cases, that application is such that the remaining motor energy is also converted to heat somewhere in the space. Consider a typical application where a motor is being used to drive a conveyor belt in a production room. The useful energy from the motor is used to overcome the friction of the rollers and belt, and the inertia of the items being moved on the conveyor, and thus is converted completely to heat. Unless the conveyor belt extends outside the space being considered, all of the motor's useful energy becomes heat inside that space. Thus, all of the energy supplied to the motor eventually becomes heat somewhere in the space being considered.

It is useful to consider the few instances where the energy from a motor is not converted completely to heat in the immediate space. This can only occur if some of the energy of the motor is stored in the product being made and leaves the space as embedded energy in the product. For example, if a motor is being used to compress a spring that is then used in a device which is further assembled, then a small part of the motor's energy is transferred to the spring in the form of potential energy. Some other examples might be energy in compressed gases, or energy in frozen foods. Although there are some cases where this energy storage and removal are involved, it is usually a very small part of the overall energy used by the motor, and for all practical considerations, all of the energy used by a motor ends up as heat in the immediate space.

The heat given off by a single phase motor—in Btu per hour—can be found as follows

$$\text{Btu/h} = \text{kW} \times \text{use factor} \times 3412\ \text{Btu/kWh} \tag{6-9}$$

or

$$\text{Btu/h} = \text{voltage} \times \text{current} \times (\text{power factor}) \times (3412\ \text{Btu/kWh}) \times \text{use factor}/(1000\ \text{wh/kWh}) \tag{6-10}$$

For a three-phase motor, the energy converted to heat per hour is given by equation 6-9 since the calculation assumes the kW rating of the motor is known. If the kW rating is not listed on the nameplate for the motor, then the voltage, current and power factor must be used, along with the factor 1.732 for proper determination of the power in a three phase motor.

$$\text{Btu/h} = \text{voltage} \times \text{current per phase} \times (\text{power factor}) \times 1.732 \times 3.412 \times \text{use factor} \tag{6-11}$$

6.4.1.5 Heating and cooling load: lighting.

Heat generated from lighting is another example in which all of the energy used is generally converted to heat in the immediate space. A very small part of the energy supplied to lights appears in the form of visible light. Incandescent lamps convert about 2-3% of the energy they use into visible light. The remaining 97% is immediately converted to heat which enters the surrounding space. Fluorescent lights are more efficient, and they convert around 10% of their input energy into visible light. Even so, the remaining 90% is converted directly into heat from the lamps and from the ballasts.

Next consider what happens to the visible light once it is produced. The photons of light strike surfaces such as floors, walls, desks, machines and people where some of the energy is absorbed and becomes heat. Some of the light energy is reflected, but it then strikes the same surfaces and more energy is converted to heat. Unless some of the light escapes outside the area of interest, all of the energy in the light eventually becomes heat. Thus, except in some relatively rare instances, all of the energy supplied to lights in an area quickly becomes heat in that same area.

In some cases, heating systems have been designed and sized to utilize the heat from lights as a significant source of heat. This is not an efficient heating strategy, but it may need to be recognized and dealt with to improve the energy efficiency of this kind of system. In other cases, light fixtures may be ventilated to the outside, or to another unheated area. Here, the heat from the lights does not contribute much of a load to the space when air conditioning is considered. However, during the heating season, this is a significant loss of heat that increases the energy that must be supplied by the regular heating system. If the ventilating ducts in the lighting fixtures can be easily closed during the heating season and reopened during the cooling season, this is an energy efficient operation strategy.

To calculate the amount of heat that is added to a space from lighting, remember that each kWh of electricity is equivalent to 3412 Btu. Thus the heat produced each hour is found by

$$\text{Btu/h} = 3412\ \text{Btu/kWh} \times \text{K kW} \tag{6-12}$$

where K is the number of kW of lighting load. Note that K must include the power consumption for any ballasts that are connected to the lights. To obtain the total heat produced from lighting, Equation 6-12 is calculated for each hour and the total obtained.

Some of the ways of reducing the amount of lighting energy needed to illuminate a space to a prescribed level include replacing lamps with more efficient lamps, cleaning the luminaries, and painting adjacent surfaces. These and other measures were discussed in detail in Chapter 5. The air conditioning savings from reducing lighting energy is illustrated in the example below.

Example 6-4: A common relamping EMO was described in Example 5-3 in Chapter Five. In that example, 200 40-Watt lamps were replaced with 34-watt lamps in a facility that was not air conditioned. If the facility had been air conditioned, there would be an additional savings depending on the number of hours that the air conditioning was needed. Calculate this additional savings assuming the air conditioner has a COP of 2.8.

Solution: Example 5-3 calculated that the energy saved from the relamping was 42,048 kWh/yr. As discussed earlier, all of this lighting energy becomes heat that must be removed by the air conditioner. If the facility is one that has a number of heat-generating machines and processes which results in the facility having to be cooled 24 hours per day, all of the lighting energy saved translates to air conditioning savings. The heat reduction from the lighting energy savings can be found using Equation 6-12 re-written as:

$$\text{Btu} = 3412\ \text{Btu/kWh} \times \text{K kW} \times \text{h}$$

$$= 3412 \text{ Btu/kWh} \times 42{,}048 \text{ kWh}$$

$$= 143.5 \times 10^6 \text{ Btu}$$

The electric energy savings from the air conditioner can now be found by dividing this Btu quantity by the EER of the air conditioner.

$$\text{A/C energy savings} = 143.5 \times 10^6 \text{ Btu}/(2.8 \times 3.412 \text{ Btu/Wh})$$

$$= 15.02 \times 10^6 \text{ Wh}$$

$$= 15{,}020 \text{ kWh}$$

A more direct way to get this same result is just to divide the lighting energy savings by the air conditioner COP.

$$\text{A/C energy savings} = 42{,}048 \text{ kWh}/2.8$$

$$= 15{,}020 \text{ kWh}$$

This increased savings from considering air conditioning makes a significant change in the cost-effectiveness of the relamping program. In this case, it increases the savings by over one-third.

6.4.1.6 Heating and cooling load: air.

The sixth major category of heating or cooling load comes from energy used to heat, cool, or humidify air. This part of the heating or cooling load can be reduced by weatherstripping, caulking, and tightening windows; by installing loading dock shelters; by replacing broken windows; and by other measures designed to reduce or eliminate air leakage to or from the outside. Air infiltration can occur through the envelope at many places, and there are infiltration-reducing techniques unique to each place. Such techniques range from caulking cracks and openings to sealing loading docks. It can also prove worthwhile to prevent airflow from conditioned areas of a plant to unconditioned areas (or vice versa) by installing airflow barriers indoors such as a plastic curtain.

Infiltration or exfiltration generally involves air moving through openings. The annual amount of energy lost through a hole or crack can be estimated from

$$\text{Btu/year} = V \times 1440 \times .075 \times .24 \times (HDD + CDD) \qquad (6\text{-}13)$$

where V = volume of air entering or leaving, in cubic feet per minute
1440 = number of minutes per day
.075 = pounds of dry air per cubic foot
.24 = specific heat of air, in Btu per pound per degree F
HDD = heating degree days per year, in days × degrees F
CDD = cooling degree days per year, in days × degrees F

This formula is a modification of that found in Reference 1. The impact of water vapor is ignored in Equation 6-13 because in many climatic regions exhausting it is often a benefit for cooling and a disbenefit for heating, and the total effect is usually negligible. In climatic areas where moisture is a problem for heating or cooling, the effect of water vapor may need to be considered.

6.4.2 Ventilation Requirements for Health

In addition to satisfying the need for a comfortable working environment, the HVAC system must also provide ventilation to remove noxious substances from the air. Many ventilation requirements are specified by state and local health and safety codes. Table 6-4 shows some of the minimum outdoor air requirements specified by ASHRAE Standard 62-1989 [11]. These requirements can often be met without having to heat or cool excessive amounts of outside air by installing special equipment such as self-ventilating hoods, or by isolating contaminant areas from other parts of a plant.

Getting rid of cigarette smoke is another problem. Where people are not smoking, the recommended ventilation standards range from 15-30 cfm/person; in smoking lounges, the recommended standard is 60 cfm/person. In this situation, the amount of ventilation air is reduced by having separate areas for smokers; a separation which is enforced by law in many states.

In Table 6-4, some applications involving air contaminants such as those from dry cleaners, and smoking areas may require additional ventilation, or at least special equipment to remove the smoke or contaminants.

6.4.3 Ventilation Standards for Comfort

One of the main reasons for using air conditioning is to keep people comfortable. The definition of a comfortable condition changes with clothing styles, the number and quantity of local drafts, and the price of energy for heating, cooling, and humidifying. Comfort is generally defined, however, by a temperature range that varies depending on the relative humid-

Table 6-4 Outdoor Air Requirements for Ventilation (From ASHRAE Standard 62-1989)

Applications	Outdoor air requirements
Offices	
Office space	20
Reception area	15
Conference room	20
Data entry area	20
Dry cleaners, Laundries	
Commercial laundry	25
Commercial dry cleaner	30
Smoking lounge	60
Bars, cocktail lounges	30

ity of the air. Three measures take advantage of the comfort zone: lowering the minimum temperature at which heating is initiated, raising the maximum temperature at which cooling is initiated, and changing the humidity in the air to more nearly conform to that of the outside environment. If outside air can be used without either humidifying or dehumidifying, considerable energy can be saved. The exact amount depends on the HVAC system, but note that evaporating 1 pound of water uses 1040 Btu. The method of cooling air so that condensation takes place and then reheating the dried air to a comfortable temperature is also costly. An alternative approach in some cases is the use of heat pipes which is discussed in Section 6.6. Another method for saving energy is to reduce the amount of ventilation air to that required by the given environment; the cube law for fan horsepower (Equation 6-14) can be used to estimate possible savings.

Note that management bears the burden of selling the employees on energy-saving measures or of introducing the changes so gradually that they are not noticed. Thus, one good method of energy management that relates to comfort is to allow temperatures to change slowly. Several studies have shown that people are relatively insensitive to slow changes in air temperature [4,5]. This insensitivity can be used to advantage by turning the air conditioning down or off 30 minutes to an hour before quitting time and letting the temperature drift.

6.5 IMPROVING THE OPERATION OF THE HVAC SYSTEM

6.5.1 Basic Operating Rules

The objective of learning how an HVAC system operates is to manage that system more efficiently. HVAC system management can be improved by careful attention to the following operating rules.

Operating Rule 1. Heat to the lowest temperature possible, and cool to the highest temperature possible. Set the hot and cold air temperatures on the hot and cold sides of a dual-duct system so that one zone is receiving only hot air and one zone is receiving only cold air. The hot temperature is thus set so that the system meets the heating needs of the coldest room and cooling needs of the warmest zone. It automatically meets the temperature needs of all the other zones.

Operating Rule 2. Avoid heating or cooling when heating or cooling is not needed. For example, heating or cooling for people is not needed when people are not in a building at times such as weekends or at night. At those times, a building temperature can be allowed to drift with the only constraint being the safe temperature of building components or other material contained within the building. Avoid heating or cooling warehouses unless they contain people or materials sensitive to heat or to cold.

Operating Rule 3. Learn how your control system is supposed to work and then maintain it properly. A consistent problem that plagues buildings is a control system that does not work. For example, a control system is not functioning as intended if return air dampers are blocked open, and the HVAC system heats or cools all the air used for ventilation. People seldom understand the way a two-thermostat system is supposed to work, and they turn the wrong thermostat, causing heating at night but none when the heating is actually needed.

Operating Rule 4. To insure that the minimum amount of ventilation air is being used, adjust the ventilation system by altering the control system settings or by changing pulleys on fans or their drive motors. One very useful relationship is

$$hp_A / hp_B = (cfm_A / cfm_B)^3 \tag{6-14}$$

This is the cube law for fan horsepower [8]. It is useful in calculating the energy consumption to be saved from reducing the ventilation requirements.

Example 6-5: ACE Industries presently has a 5-hp ventilating fan that draws warm air from a production area. The motor recently failed and they think they can replace it with a smaller motor. They have determined that they can reduce the amount of ventilation air by one third. What size motor is needed now?

Solution: Use Equation 6-14, and note that the ratio of the new to old cfm rate is 2/3. Thus, the new hp needed is:

$$\text{New hp} = (2/3)^3 \times 5 \text{ hp} = 0.3 \times 5 \text{ hp} = 1.5 \text{ hp}$$

Since 1 hp is equivalent to .746 kW at 100% efficiency, the power savings achieved by a reduction of H hp is given by

$$\text{Power saved (kW)} = (\text{H hp} \times .746 \text{ kW/hp})/\text{EFF} \qquad (6\text{-}15)$$

where EFF is the motor efficiency, usually between .70 and .90. This expression can only be used if the old and new motors have the same efficiencies. If this motor is running constantly, the action of reducing the fan horsepower reduces both the demand and the energy part of the electric bill; otherwise it may affect the demand but must be multiplied by the hours of use to determine the amount and cost of energy saved.

Example 6-6: What is the electrical load reduction for the smaller fan motor in Example 6-5 if the 5-hp motor had an efficiency of 84%? The new 1.5-hp motor has an efficiency of 85.2%.

Solution: We cannot use Equation 6-15 since the two motors do not have the same efficiency. We must calculate the electrical load from each motor and determine the difference.

$$\text{Old load} = (5 \text{ hp}) \times (0.746 \text{ kW/hp})/(0.84) = 4.44 \text{ kW}$$

$$\text{New load} = (1.5 \text{ hp}) \times (0.746 \text{ kW/hp})/(0.852) = 1.31 \text{ kW}$$

$$\text{Electric load reduction} = \underline{3.13 \text{ kW}}$$

However, since the two motor efficiencies are approximately equal, we can make an approximation by using Equation 6-15:

$$\text{Motor load reduction} = (3.5 \text{ hp}) \times (0.746 \text{ kW/hp})/(0.84) = \underline{3.11 \text{ kW}}$$

This is very close to the correct value.

Operating Rule 5. If you do not need heating, cooling or ventilation, turn off the HVAC system. Unnecessary conditioning and ventilation cost money. Find out when the conditioning and ventilation is needed and arrange to have the HVAC system running only at those times.

6.5.2 Inspecting the HVAC system

First, the auditor should determine whether the room is being cooled or heated more than is necessary. Ideally, a person in a jacket should be comfortable in the winter, and a person in shirt sleeves should be comfortable in the summer. Excessive heating or cooling is another unnecessary energy cost.

Next, the energy auditor must inspect the HVAC system thoroughly to determine whether it is operating properly. Every HVAC system has heat transfer surfaces to enable heating or cooling to take place, every HVAC system has some means of transporting its working fluid to the point of use from the point where heating or cooling is supplied, and every HVAC system has a set of controls which govern its operation. Inspecting each one of these component areas is necessary in a complete energy audit. Since the most common systems are those in which air is the working fluid, the rest of this discussion will be confined to air-cooled systems.

6.5.2.1 Heat transfer surfaces

A heat transfer surface is the surface where a hot or cold fluid gives up or receives heat from air that is passing around it. Typically, heat transfer surfaces are designed so that a hot or cold liquid flows through pipes surrounded by fins. The fins are used to increase the heat transfer rate. These heat transfer surfaces must be examined periodically and be maintained to continue to work properly. The points to be inspected in this part of the HVAC system are the fluid flow lines and the heat transfer surfaces. Do relevant gauges show that fluid is flowing? Are "hot water" pipes actually hot? Can you hear the sound of fluid flowing? When you examine the heat transfer surfaces, are the fins and coils clean, or are they fouled with dirt or grease or dust? Fins must be clean to function effectively and efficiently.

6.5.2.2 Air transportation system

The air transportation system moves air from the outside, mixes outside air with return air, and removes used air either to the outside or to the supply fans for use as return air. The main components of this system are the ductwork, dampers, and filters and the fans, blowers, and associated motors. The ductwork can have insulation hanging loose. The ducts can leak air through untaped seams, or they can be crushed by adjacent piping. Loose insulation can be detected by removing one duct panel and examining the inside of the duct with a flashlight; untaped seams and crushed ducts can be detected with a quick visual inspection. Dampers and filters can also be inspected visually. The dampers should be clean and should close, and their mechanical linkages should be connected to the control actuators. Filters should be installed and reasonably clean; return air grilles should also be inspected to see whether they need to be cleaned. Filters should be cleaned or changed at periodic intervals.

The HVAC fans and blowers should be examined carefully. Fans and blowers should be operational, and the belts should be aligned correctly so that the fan pulley and the motor pulley are in a straight line. Be particularly thorough in examining fan belts and motor connections; the authors have observed instances where motors had been installed and were running but were not connected to the fans they were supposed to drive. Motors should also be inspected to see that they are properly connected with balanced voltages to all three legs of a three-phase system. Motors should also be free from excess bearing noise. Fans or blowers should be reasonably clean, since accumulated dust detracts from their efficiency. The fan or blower should rotate in the correct direction, and the fan shaft should not bind.

6.5.2.3 The control system

The HVAC control system detects pressures or temperatures and compares these with preset values. Depending on the result, the control system sends electrical or pneumatic signals to open or close dampers, open or close valves, and turn furnaces, chillers, and blower motors on or off. Clearly it is important that the control system function properly; otherwise, the HVAC system does not work as intended, and will not be energy efficient.

The first step in inspecting the control system is to examine the thermostats. A reliable industrial thermometer can be used to calibrate each thermostat thermometer; if the temperature difference between the two temperature readings is significant, the thermostat should be checked by a vendor. Next the thermostat set temperature should be raised and lowered to see if the heat or cold comes on or shuts off; this procedure tests the entire HVAC control system.

Gauges should be checked to see whether they are connected and whether they are reading within the correct operating ranges. The compressor that supplies compressed air to the control system should be inspected to see that it is working properly and not leaking oil or water into the control system; if either oil or water gets into the controls, a complete replacement of the control system is often necessary. An air dryer is almost always a necessity on the air supply system to keep the controls working properly.

6.6 HEAT PIPES

In many areas of the country, removing humidity is the chief energy cost of air conditioning. This is because moisture is condensed out of the air by the cooling coil and the colder the air when it passes over the cooling coil, the more moisture is removed. Therefore, in areas where the humidity is high, the air must be cooled much lower than the desired temperature in order to remove the moisture and then heated back to the desired temperature. This means that energy is required to overcool the air; additional energy is required to reheat the air; and the equipment must be oversized in order to overcool the air which increases the power demand of the air conditioning system.

The older, energy-inefficient air-conditioners were designed with very cold cooling coils; newer, high-efficiency models are often designed with warmer coils. These coils are larger and require less energy to operate, and one of the reasons why they save energy is because they do not remove as much moisture. Although this is not a problem in some parts of the country, in areas with high humidity the energy-efficient air-conditioners often leave the conditioned air uncomfortably humid. This problem is generally solved by lowering the temperature setting of the thermostat which uses additional cooling energy and may negate the savings from the energy efficient model.

One energy savings solution is the heat pipe [12]. Heat pipes are relatively new on the commercial air conditioning scene. Although they were first developed near the turn of the century, their commercial use only recently became feasible as a result of research on a NASA contract. A heat pipe is a metal tube that is filled with an evaporative fluid and then sealed at both ends. When heat is applied to one end of the tube, the fluid inside evaporates and the vapor moves to the other, cooler end. The vapor then condenses in the cooler end and returns to the warmer end by gravity or by some sort of capillary action through an inside wick. The heat pipe is activated by the temperature difference between the two ends and does not use energy to operate. See Figure 6-5.

When used in an air conditioning system, one end of the heat pipe is placed in the return air system and is heated by the warm return air. That

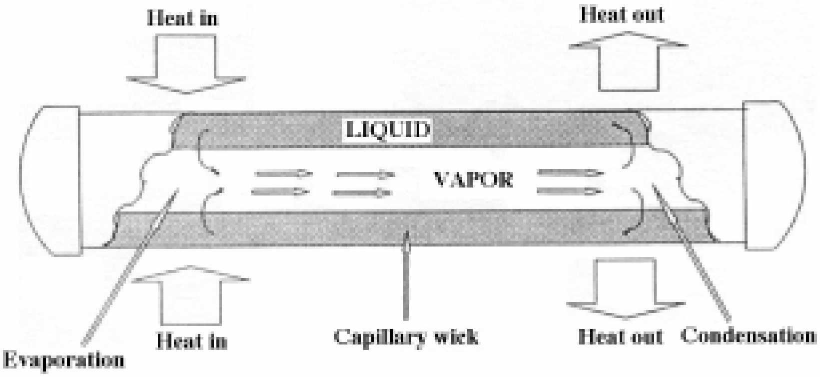

Figure 6-5. Diagram of heat pipe.

heat is "free" because no additional energy is expended to generate the heat. Because the heat pipe absorbs heat from the return air, that air is cooler when it goes to the cooling coil so the cooling coil can work at a lower temperature. That means that the cooling coil can remove more moisture from the air; it also means that the cooling load on the compressor is lower. The other end of the heat pipe is placed in the supply, or conditioned, air system. The heat from the first section in the return air stream is transferred to this section which is used to reheat the chilled air and lower the humidity before the air is distributed throughout the system. The process of reheating the air causes that end of the heat pipe to become chilled. See Figure 6-6.

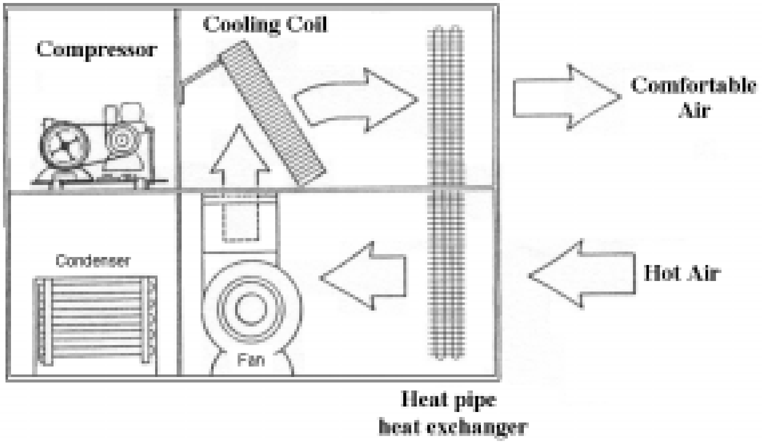

Figure 6-6.
A high-efficiency air conditioner/dehumidifier using heat pipes.
Courtesy of Florida Solar Energy Center.

Heat pipes are also useful for areas which need large amounts of outside air for ventilation. Fresh air brings in both heat and humidity which means that larger air conditioning systems are usually needed. The addition of heat pipes to the air conditioning system allows the addition of up to 20% fresh air without increasing the size of the system.

Heat pipes are suitable for a number of air conditioning situations. Industries which require a low humidity level or humidity control include: electronic component production, assembly and storage; film drying, processing and storage; drug, chemical and paper manufacturing and storage; printing; candy and chocolate processing and storage. Other examples of industries or areas which would benefit from heat pipes are hospital operating rooms, libraries, grocery stores, telephone exchanges and relay stations, clean rooms, underground silos, and places with indoor swimming pool or spa facilities.

6.7 THERMAL STORAGE

Thermal energy storage offers one of the most promising technologies for effective electrical peak load management in buildings and other facilities [13]. Heating and cooling energy needs provided by electrically powered equipment usually correspond to the time of a facility's peak demand, and contribute to increased electric costs that occur from the demand charge. A thermal energy storage system may produce chilled water or ice off-peak for later use in cooling a facility, or produce heated air or water off-peak for later use in heating a facility.

Cool storage systems operate by producing and storing chilled water or ice during the evening and night when electric rates are low, and drawing on that stored water or ice during the day when the cooling load is greatest. The high-demand electrically powered chillers are shifted to operation during off-peak periods, and are especially cost-effective for facilities that have time-of-day rates which offer low-cost energy during the night. The storage of chilled water or ice also allows the facility to operate with smaller-sized chillers since the peak cooling load is handled with the combination of the small chiller and the cool storage. For new buildings or facilities, this reduction in the size of the chillers often pays most of the cost for the cool storage system. Other cooling system operating cost savings also result from this approach because of the downsizing of fans, pumps and ducts due to the lower temperatures of distributed air because of the very low temperatures of the stored water or ice.

Thermal energy storage systems typically increase the overall system energy consumption because of the storage losses, but they also significantly decrease the costs associated with peak load or peak demand charges. The increase in energy for cooling with storage is often moderated due to the higher efficiency of the chiller system operating at lower night time temperatures.

Many electric utilities offer rebates or incentives for facilities to install thermal storage systems. The incentive may be in the form of low rates for off-peak energy use, or in the form of a direct rebate based on the number of kW moved off-peak.

6.8 SUMMARY

In this chapter, we have explained the functions and the components of HVAC systems. Once the functions and components are understood, the energy manager can find ways to reduce the heating and cooling loads and thus reduce this element of energy costs. When the manager also understands how each of the HVAC system components works, he or she is then prepared to improve the operation of the physical system. By using the operating rules presented, and by adding additional rules unique to your own system, this understanding can be translated into improved operating policies for both HVAC equipment and for the people affected by the HVAC system.

REFERENCES

1. *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Ga., 1993.
2. Donald Rapp, *Solar Energy*, Prentice-Hall, Englewood Cliffs, N.J., 1981.
3. W.J. Kennedy, Jr., and Richard E. Turley, “Scheduling and the Energy Economics of Wall Design,” in *Proceedings of the 1981 Spring Annual Conference & World Productivity Conference*, Detroit, Michigan, Institute of Industrial Engineers, Atlanta, Ga., 1981.
4. Larry G. Berglund and Richard R. Gonzalez, “Human Response to Temperature Drift,” *ASHRAE Journal*, Aug. 1978, pp. 38-41.
5. L.G. Berglund, and R.R. Gonzalez, “Application of Acceptable Temperature Drifts to Built Environments as a Mode of Energy Conservation,” *ASHRAE Transactions*, Vol. 84, Part 1, 1978.
6. National Electric Contractors Association and National Electrical Manufacturers Association, *Total Energy Management: A Practical Handbook on Energy Conservation and Management*, Third Edition,

National Electrical Contractors Association, Washington, D.C., 1986.

7. *ASHRAE Handbook for Systems and Equipment*, American Society of Heating, Refrigerating,, and Air Conditioning Engineers, Atlanta, Ga., 1992.
8. *ASHRAE Handbook for HVAC Applications*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Ga., 1991.
9. *CFC's: Time of Transition*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, 1989.
10. Energy Policy Act of 1992, P.L. 102-486 (HR 776), U.S. Congress, October 24, 1992.
11. ANSI/ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Ga., 1989.
12. *Commercial High Efficiency Dehumidification Systems Using Heat Pipes, A Technical Manual*, Heat Pipe Technology Company, Alachua, FL, 1993.
13. "Thermal Storage Forum," *ASHRAE Journal*, April, 1990, pp 26-66, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

BIBLIOGRAPHY

Frank E. Beaty, *Sourcebook of HVAC Details*, McGraw-Hill Book Company, New York, NY, 1987.

Robert Chatenver, *Air Conditioning and Refrigeration for the Professional*, Wiley, New York, NY, 1988.

Harold R. Colen, *HVAC System Evaluation*, R.S. Means Company, Kingston, MA, 1990.

Roger W. Haines, *HVAC System Design Handbook*, TAB Professional and Reference Books, Blue Ridge Summit, PA, 1988.

HVAC Systems—Applications, Sheet Metal and Air Conditioning Contractors National Association, Vienna, VA, 1987.

Industrial Ventilation, Committee on Industrial Ventilation, American Conference of Governmental Industrial Hygienists, Lansing MI, 1979.

John I. Levenhagen, *HVAC Controls and Systems*, McGraw-Hill Book Company, New York, NY, 1993.

Raymond K. Schneider, *HVAC Control Systems, Second Edition*, Wiley, New York, NY, 1988.

Variable Air Volume Systems Manual, 1980 ed., Honeywell, Inc., Minneapolis, 1980.