ENERGY EFFICIENT SYSTEMS AND STRATEGIES FOR HEATING, VENTILATING, AND AIR CONDITIONING (HVAC) OF BUILDINGS

Moncef Krarti, PhD, PE[1]

INTRODUCTION

The heating, ventilating, and air conditioning (HVAC) systems maintain and control temperature and humidity levels to provide an adequate indoor environment for people activity or for processing goods. The cost of operating an HVAC system can be significant in commercial buildings and in some industrial facilities. In the U.S., it is estimated that the energy used to operate HVAC systems can represent about 50% of the total electrical energy use in a typical commercial building (Krarti, 2000). It is therefore important that buildings designers recognize some of the characteristics of the HVAC systems and determine if any available design and operating options can be considered to improve the energy of these systems.

A basic HVAC air distribution system consists of an air-handling unit with the following components as shown in Figure 1:

- *Dampers to control the amount of air to be distributed by the HVAC system including: outside air (OA) damper, return air (RA) damper, exhaust air (EA) damper, and supply air (SA) damper.*
- *Preheat coil in case the outside air is too cold to avoid any freezing problems.*
- *Filter to clear the air from any dirt.*
- *Cooling coils to condition the supply air to meet the cooling load of the conditioned spaces.*
- *Humidifiers to add moisture to the supply air in case a humidity control is provided to the conditioned spaces.*
- *A distribution system (i.e., ducts) where the air is channeled to various locations and spaces.*

Each of the above listed components is available in several types and styles. The integration of all the components constitutes the secondary HVAC system for the sole purpose of conditioned air distribution.

The main objectives of the HVAC systems installed within buildings include:

- *maintaining thermal comfort for all building occupants. In most climates, HVAC systems have to meet both heating and cooling requirements.*
- *providing fresh air intake (i.e., ventilation) to maintain acceptable indoor air quality.*

In the following sections, energy efficient alternatives for HVAC systems and operating and control strategies are presented. These alternatives should be considered in the early stages of designing sustainable buildings.

DEMAND CONTROLLED VENTILATION

The energy required to condition ventilation air can be significant in commercial buildings especially in locations with extreme weather conditions. While ventilation is used to provide fresh air to occupants in commercial buildings, it is used to control the level of dust, gases, fumes, or vapors in several industrial applications. The existing volume of fresh air should be estimated and compared with the amount of ventilation air that is required by the applicable standards and codes. Excess in air ventilation should be reduced as it can lead to increases in heating and/or cooling loads. However, in some climates and periods of the year or the day, providing more air ventilation can be beneficial and may actually reduce cooling and heating loads through the use of air-side economizer cycles.

[1]Civil, Environmental, and Architectural Engineering Department, University of Colorado, Boulder, CO 80309, moncef.krarti@colorado.edu.

FIGURE 1. Typical Air Handling Unit for an air HVAC system.

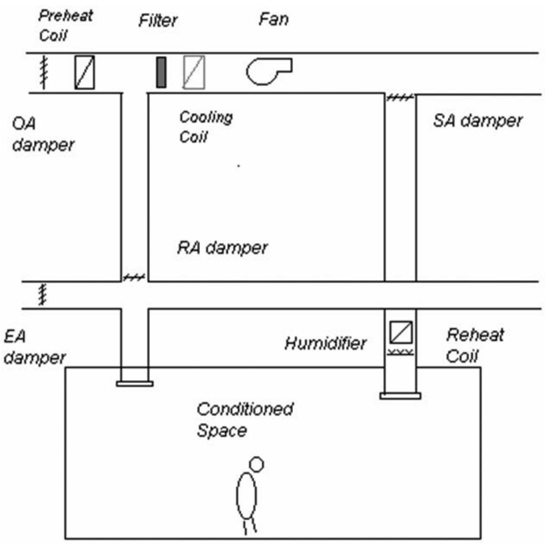


Table 1 summarizes some of the minimum outdoor air requirements for selected spaces in commercial buildings.

If excess ventilation air is found, the outside air damper setting can be adjusted to supply the appropriate air ventilation rates that meet the minimum outside requirements as listed in Table 1. Further reductions in outdoor air can be obtained by using demand ventilation controls that supply outside air only during periods when there is need for fresh air. A popular approach for demand ventilation is the monitoring of CO_2 and/or CO concentration level within the spaces. CO_2 is considered a good indicator of pollutants generated by occupants inside commercial buildings. The outside air damper position is controlled to maintain a CO_2 set-point within the space. CO_2-based demand-controlled ventilation has been implemented in various buildings with intermittent occupancy patterns including cinemas, theaters, classrooms, meeting rooms, and retail establishments. Furthermore, air ventilation intake for several office buildings has been controlled using CO_2 measurement (Emmerich and Persiley, 1997). Based on field studies, it has been found that significant energy savings can be obtained with a proper implementation of CO_2-based demand-controlled ventilation. Typically, the following building features are required for an effective performance of demand ventilation controls (Alalawi and Krarti, 2003):

- Unpredictable variations in the occupancy patterns
- Requirement of either heating or cooling for most of the year
- Low pollutant emissions from non-occupant sources (i.e., furniture, equipment, etc)

It should be noted that while CO_2 can be used to control occupant-generated contaminants, it may not be reliable to control pollutants generated from non-occupant sources such as building materials. As a solution, a base ventilation rate can be maintained at all times to ensure that non-occupant contaminants are controlled within acceptable concentration levels.

Fully enclosed parking garages are usually underground and require mechanical ventilation. Indeed, in the absence of ventilation, enclosed parking facilities present several indoor air quality problems. The most serious is the emission of high levels of carbon monoxide (CO) by cars within the parking garages. Other concerns related to enclosed garages are the presence of oil and gasoline fumes, and other contaminants such as oxides of nitrogen (NOx) and smoke haze from diesel engines.

To determine the adequate ventilation rate for garages, two factors are typically considered: the

TABLE 1. Minimum ventilation rate requirements for selected spaces in commercial buildings.

Space and or Application	Minimum Outside Air Requirements	Reference
Office Spaces	9.5 L/s (20 cfm) per person	ASHRAE Standard 62
Corridors	0.25 L/s per m^2 (0.05 cfm/ft^2)	
Restrooms	24 L/s (50 cfm) per toilet	
Smoking Lounges	28.5 L/s (60 cfm) per person	
Parking Garages	7.5 L/s per m^2 (1.5 cfm/ft^2)	

number of cars in operation and the emission quantities. The number of cars in operation depends on the type of the facility served by the parking garage and may vary from 3% (in shopping areas) up to 20% (in sports stadiums) of the total vehicle capacity (ASHRAE, 2007). The emission of carbon monoxide depends on individual cars including such factors as the age of the car, the engine power, and the level of car maintenance.

For enclosed parking facilities, ASHRAE standard 62 specifies a fixed ventilation rate of 7.62 L/s.m^2 (1.5 cfm/ft^2) of gross floor area (15). Therefore, a ventilation flow of about 11.25 air changes per hour is required for garages with 2.5 m ceiling height. However, some of the model code authorities specify an air change rate of 4 to 6 air changes per hour. Some of the model code authorities allow ventilation rates to vary and be reduced to save fan energy if CO-demand controlled ventilation is implemented, that is, when a continuous monitoring of CO concentrations is conducted, with the monitoring system being interlocked with the mechanical exhaust equipment. The acceptable level of contaminant concentrations varies significantly from code to code (Krarti and Ayari, 1998). Krarti and Ayari (2001) have developed a general methodology to determine the ventilation requirements for parking garages.

FIGURE 2. Typical energy savings and maximum CO level obtained for demand CO-ventilation controls.

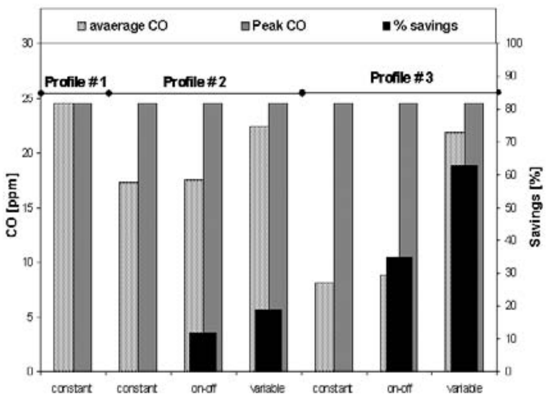
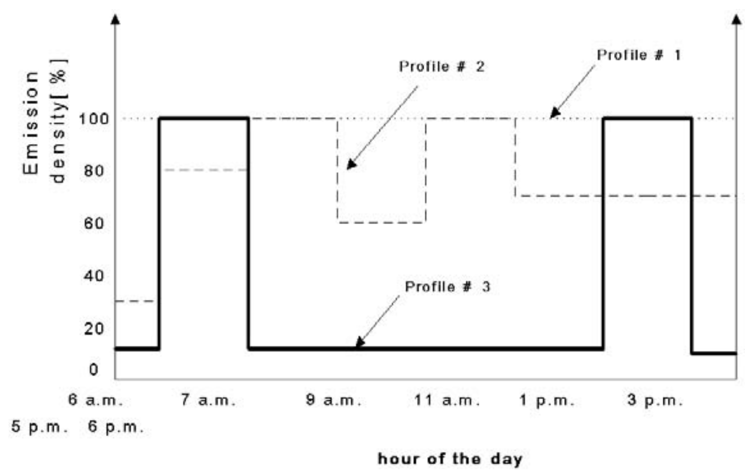


Figure 2 also indicates the fan energy savings achieved by the On-Off and VAV systems (relative to the fan energy use by the CV system). As illustrated in Figure 2, when CO emission density varies strongly over the course of the day, significant fan energy savings can be obtained when demand CO-ventilation control strategy is used to operate the ventilation system, while maintaining acceptable CO levels within the enclosed parking facility. These energy savings depend on the pattern of car movement within the parking facility. Figure 3 indicates three types of car movement profiles considered in the analysis (Ayari et al., 2000).

NIGHT VENTILATION

Several studies have investigated the benefits of night ventilation on improving thermal comfort and reducing cooling loads in commercial buildings. In particular, Kammerud et al. (1984) and Kolokotroni

FIGURE 3. Car movement profiles used in the analysis conducted in reference (Ayari et al., 2000).



and Aronis (1999) have reported that night ventilation, combined with thermal mass, affects building internal conditions during typical cooling days in two ways:

- A reduction in peak indoor air-temperatures.
- A time lag between the maximum outdoor and indoor temperatures.

Xiang and Krarti (2007) have proposed a simplified analysis method to estimate the percent cooling energy saving f_d associated with night ventilation for a typical office building using the following expression:

$$f_d = C_1 \cdot \left(1 - e^{-C_2 \cdot t}\right) \cdot \left(1 - e^{-C_3 \cdot \left(1 - e^{-C_4 \cdot t}\right) \cdot n}\right) \qquad (1)$$

where n is the ventilation flow rate expressed in ACH and t the ventilation period length in hours. The correlation coefficients C_1, C_2, C_3, and C_4 depend on the location of the building.

Table 2 lists the values of the correlation coefficients for the four U.S. sites. Figure 4 depicts graphically the variation of the percent cooling energy savings as a function of both ventilation rate and ventilation period length when the office building is located in Miami, FL.

It should be noted that the coefficient C_1 determines the maximum possible cooling energy saving due to night ventilation. Denver has a high C_1 value due to its large temperature difference between day and night. The mild summer average temperature in San Francisco also favors night ventilation and explains the high C_1 value. Miami, with high average outdoor temperatures and small day-and-night temperature difference during the summer, is not a favorable climate for night ventilation. Night ventilation has the potential to save about 26% of annual cooling energy use for an office building located in Chicago.

TABLE 2. Correlation coefficients of Eq. (1) for four U.S. cities.

Site	C_1	C_2	C_3	C_4
Denver	32.5	0.31	0.60	0.50
San Francisco	35.7	0.23	0.68	0.40
Miami	9.0	0.43	0.56	0.47
Chicago	26.8	0.27	0.69	0.42

BUILDING MASS THERMAL STORAGE

The thermal storage capabilities inherent in the mass of a building structure can have a significant effect on the temperature within the space as well as on the performance and operation of the HVAC system. Effective use of structural mass for thermal storage reduces building energy consumption and reduces and delays peak heating and cooling loads. Perhaps the best-known use of thermal mass to reduce energy consumption is in buildings that include passive solar techniques (Balcomb, 1983).

Cooling energy can be reduced by pre-cooling the structure at night using ventilation air. Braun

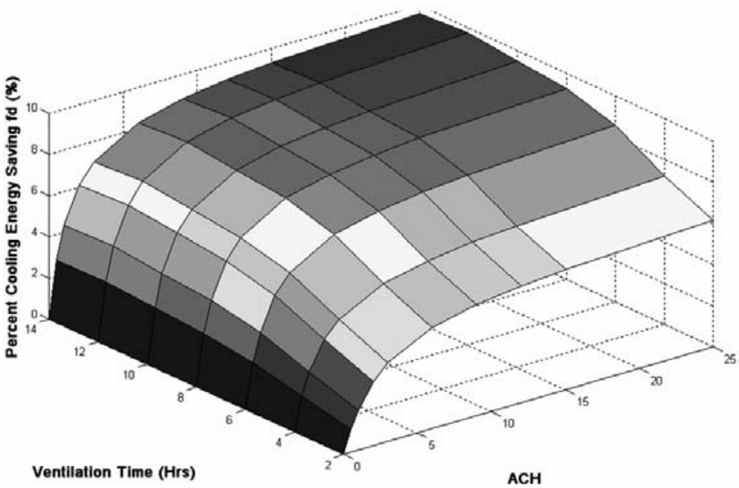


FIGURE 4. Percent cooling energy saving vs. ACH and ventilation period length when the building is located in Miami, FL.

(1990) suggested that mechanical pre-cooling of a building can reduce and delay peak cooling demand. Simmonds (1991) suggested that the correct building configuration may even eliminate the need for a cooling plant. Mechanical pre-cooling may require more energy use; however, the reduction in electrical demand costs may give lower overall energy costs. Moreover, the installed capacity of air-conditioning equipment may also be reduced, providing lower installation costs. Braun (2003) provided an overview of related research, and found that 1) there is a tremendous opportunity for reductions in on-peak energy and peak demand and 2) the savings potential is very sensitive to the utility rates, building and plant characteristics, weather conditions, and occupancy schedule.

The potential energy cost savings from pre-cooling depends on the control strategies utilized to charge and discharge the building thermal mass. Several studies of building pre-cooling controls have been reported (Braun, 1990; Rabl and Norford, 1991; Braun et al., 2001; and Morgan and Krarti, 2006). The potential of pre-cooling in reducing electric energy costs is generally well documented. Reported investigations have shown that energy costs have been reduced by up to 50% under favorable utility rate structures while on-peak demand has been reduced by up to 35% just by pre-cooling building thermal mass.

In particular, Morgan and Krarti (2006) have performed both simulation analyses and field testing to evaluate various pre-cooling strategies. They found that the energy cost savings associated to pre-cooling thermal mass depends on several factors, including thermal mass level, climate, and utility rate. For time-of-use utility rates, they found that the energy cost savings are affected by the ratio of on-peak to off-peak demand charges, R_d, as well as the ratio of on-peak to off-peak energy charges, R_e. Figures 5 and 6 show the variation of the annual en-

FIGURE 5. Annual energy cost savings due to pre-cooling, relative to conventional controls, as a function of R_e.

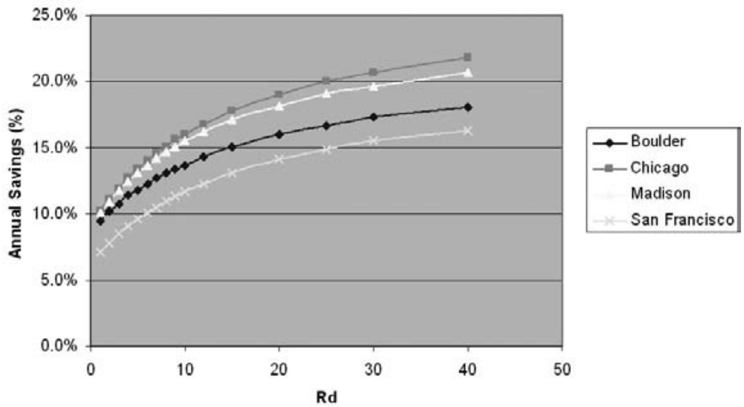
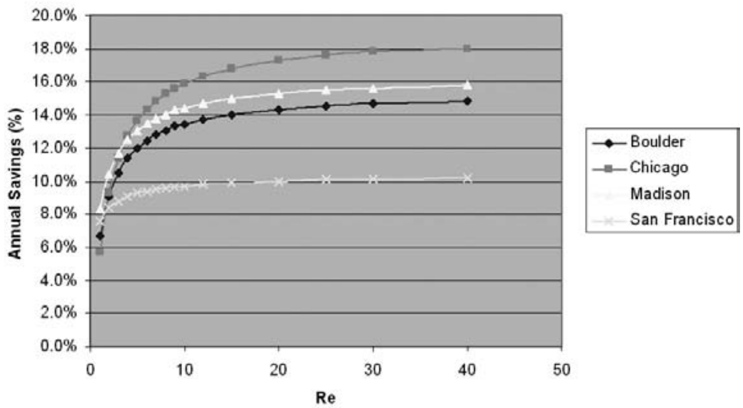


FIGURE 6. Annual energy cost savings due to pre-cooling, relative to conventional controls, as a function of R_d.



ergy cost savings due to 4-hr pre-cooling an office building with heavy mass as a function of R_d and R_e, respectively.

It should be noted that the effective use of thermal mass can be considered either:

- incidental and not to be considered in the heating or cooling design, or
- intentional and form an integral part of the design.

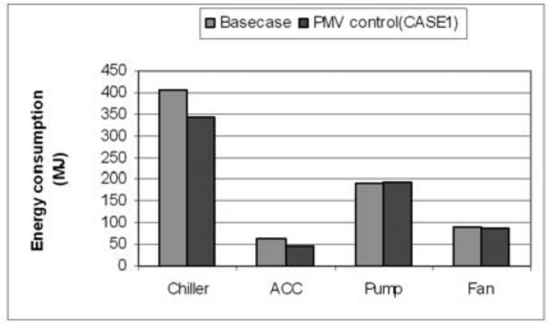
THERMAL COMFORT BASED CONTROLS

Thermal comfort-based controls have been proposed as alternatives to temperature-based controls for HVAC systems to maintain better thermal comfort within indoor environments. Several factors can affect indoor thermal comfort including air temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing level (ASHRAE, 2001). Various models have been suggested to estimate a single indicator to describe thermal comfort within buildings. The most commonly used and probably the best understood model is the PMV model developed and later refined by Fanger (1972). The PMV model is based on empirical correlations to predict the mean response of a large group of people according to the ASHRAE thermal sensation scale that ranges from –3 (very cold) to 3 (very hot). The recommended indoor thermal comfort for sedentary of slightly active persons ranges from –0.5 to 0.5 (ASHRAE Standard 55, 1981; and ISO standard 7730, 1984).

Several analyses based on simulation results have indicated that thermal comfort-based controls can provide superior thermal comfort to occupants compared to the conventional control strategies (Wai et al., 2000; Zhai et al., 2002; and Brunello et al., 2003).

Mun and Krarti have performed a controlled experimental investigation to assess the potential of energy savings associated with PMV-controlled systems. Figure 7 compares the electrical energy use by an air system operated using a temperature-based control (basecase) and a radiant cooling system operated using a thermal comfort-based control (case-1). The results show that the radiant system with thermal comfort-based control can save 40% of the total HVAC electrical consumption relative to a conventional air system controlled using a thermostat.

FIGURE 7. Comparison of electrical energy consumption for HVAC equipment for air system and radiant cooling system.



INDIVIDUALLY-CONTROLLED AIR CONDITIONING SYSTEMS

Conventional centralized HVAC systems in large buildings are controlled by thermostats that are usually installed in selected spaces. Individuals typically cannot adjust the volume and direction of the supplied air according to the personalized needs of each occupant. Furthermore, airflow supplied from centralized systems may be blocked by cubicle partitions, cabinets, and furniture. Recently, there is an increasing interest in HVAC systems that can individually condition the immediate environment of occupants, while the ambient space is controlled by the central system to maintain marginally acceptable thermal comfort conditions. Among these systems are the so-called "task/ambient conditioning" (TAC) systems. A typical TAC system is an individually-controllable under-floor air supply system where occupants can control the volume and direction of the air distributed from diffusers on a raised floor. An alternative TAC system is a personalized environmental module that has supply air diffusers on the desk. Occupants can control not only the air direction but also the air temperature and the air speed. The newest TAC system is a partition type fan coil unit that incorporates the function of a fan coil unit and multiple split air conditioners into a regular partition. Such partition walls are used to distribute supply air to occupied spaces (Pan, 2005).

Figure 8 shows a schematic diagram for a TAC system. Conditioned air from the air-handling unit (AHU) flows into the under-floor plenum through

FIGURE 8. Schematic diagram for a TAC system (EA: Exhaust Air; OA: Outside Air Intake; SA: Supply Air; RA: Return Air; M: Motorized damper).

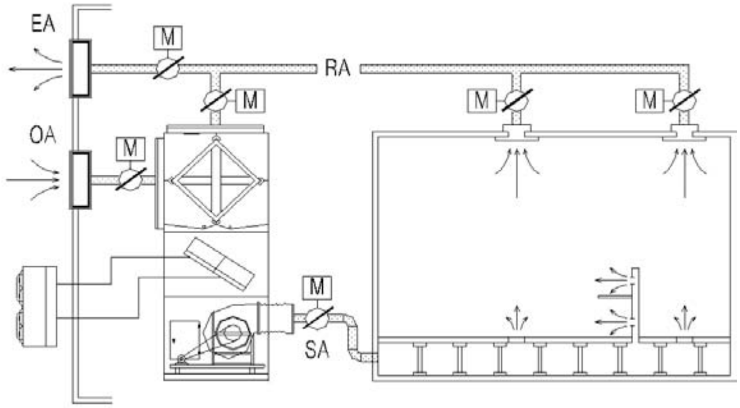
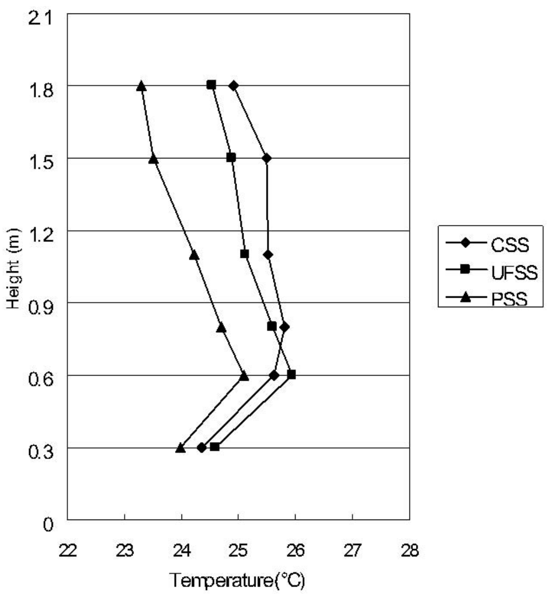


FIGURE 9. Vertical temperature distributions for three air supply systems.



a flexible duct. A fan unit installed in the partition panel draws the air from the under-floor plenum to the occupied zone through passageways in the partition panels and outlet grilles on the partitions. Conditioned air can also be directly supplied from floor diffusers, serving as an under-floor supply system. The room air will be exhausted through ceiling vents.

The thermal performance under cooling conditions for three air supply systems: ceiling supply system (CSS), under-floor supply system (UFSS), and partition supply system (PSS) have been carried by Jeong et al. (2006a) using both experimental and simulation analyses. Figure 9 compares the temperature stratification of the three air supply systems. As indicated in Figure 9, the indoor temperature associated with the partition supply system (PSS) is generally lower than those obtained with the ceiling supply system (CSS) and the under-floor supply system (UFSS). The testing analysis indicated that PSS can reach the desired room temperature setting within the personal task area sooner than CSS and UFSS.

It should be noted that the partition air supply system allows the occupant to turn on/off and to control the air speed and direction of the supplied air. In other words, the occupant can control airflow to reduce the discomfort caused by unwanted drafts.

Figure 10 shows the temperature within a typical office space served by a TAC system for two values of air supply temperatures (Jeong et al., 2006b). Figure 10 clearly indicates that the heat from the body and the monitor flows upward and backward to the back of the occupant as the TAC system delivers air to the front of the occupant. The results shown in Fig. 10 confirm that the case with higher supply air temperature has lower head-foot temperature gradient than that obtained for cases with lower supply air temperatures.

OTHER TECHNOLOGIES

In this section, other HVAC systems and technologies are briefly outlined. A more detailed description of these technologies can be found in Krarti (2000).

(a) Case with supply air temperature of 22°.

(b) Case with supply air temperature of 24°.

FIGURE 10. Space temperature distributions for an office space with a seated occupant.

Thermal Energy Storage (TES) systems

Thermal energy storage or TES systems can effectively be used to shift heating or cooling loads from one period to another period. A properly designed and installed thermal storage system has several benefits including reduction of operating costs, reduction of the size of the cooling or heating generating equipment, and increase in operating flexibility.

Thermal energy storage can be achieved by two mechanisms:

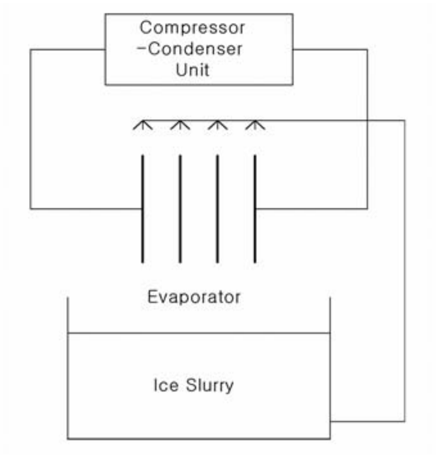
1. Sensible energy storage by increasing (for heating applications) or decreasing (for cooling applications) the temperature of the storage medium (water for instance).
2. Latent energy storage by changing the phase of the storage medium (Phase Change Materials –PCM–, eutectic salt solutions, or ice-water mixtures).

For cooling applications, there are several types of TES systems that have been installed in various commercial buildings and industrial applications. Among these TES systems are:

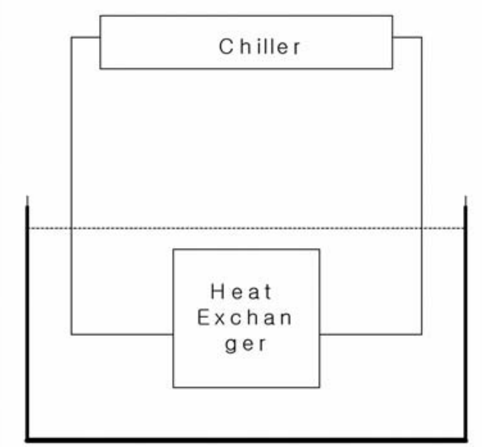
- Chilled Water Storage systems: These systems consist typically of tanks where chilled water (temperature above freezing point) is stored before it is used during off-peak periods. There is no change of phase for the water in these systems and thus can store a limited density of energy. Water is selected since it has the highest specific heat of all common materials (4.18 kJ/kg(C). Typically, a tank volume varying from 0.09 to 0.17 m^3 is required to store 1 kWh of energy using chilled water.

- Eutectic Salts: In these systems, a solution of salts is used to store energy at low temperatures. The advantage of these systems is that temperature below 0°C can be achieved before the solution is frozen. In addition, some salts have heat of fusion comparable to that of ice. It should be noted that the solution of salts needs to be mixed in a controlled ratio to ensure that the mixture melts completely and has the same composition in both liquid and solid phases. For eutectic salts, the volume requirement for the storage tank is estimated to be 0.05 m^3/kWh.
- Ice Storage Systems: In these systems, the water is transformed into ice that is stored in tanks. Therefore, the water can be present in the form of two phases (liquid and solid) inside the tank. Typically, the ice is made during the off-peak periods (charging) and is melted during on-peak periods (discharging). Ice storage systems have higher energy density compared to chilled water systems. Thus, the volume of the storage tank required for ice systems is significantly less than that for chilled water systems (almost one-fourth). In addition, ice storage systems allow for innovative HVAC system design such as cold air distribution systems that have lower initial costs compared to conventional distribution systems. Common ice storage systems include:
    - Ice harvesters (Figure 11a). In these systems, thin ice layers are formed around vertical plates (evaporator) that are sprayed with water that is pumped from the tank. The ice layers are harvested to the storage tank by circulating hot gases through the evaporator. The ice mixed with water is stored in the tank to obtain what is often referred to as ice slurry. The volume requirement for the storage tank used in ice harvesters is about 0.025 m^3/kWh.

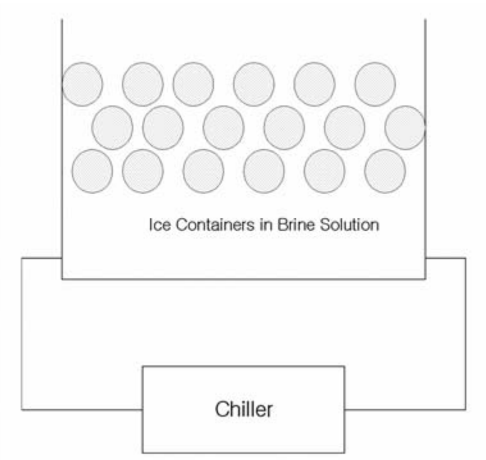
FIGURE 11. Commonly installed ice storage systems.



(a) Ice harvester storage system.



(b) Ice-on-coil with internal melt storage system.



(c) Containerized ice storage system.

- Internal melt ice-on-soil storage systems (see Figure 11b). In these systems, direct expansion coils are fitted inside the storage tank that is filled with water. Brine solution (mixture of water and ethylene glycol) is typically circulated through the coils with a temperature in the range of –6°C to –3°C. In the charging mode, ice layers are formed around the coils. In the discharging mode, ice is melted by circulating brine solution in the tank's coils. The brine solution is then cooled and used to provide for space cooling. The volume of the storage tank required for internal melt ice-on-coil systems varies from 0.019 to 0.023 m^3/kWh.
- External melt ice-on-coil storage systems. They are similar to the internal melt ice-on-coil system in that the ice is made around coils filled with brine solution. However, the water that results from melting ice in the storage tank is directly used to provide space cooling. Typically, a volume of 0.023 m^3/kWh is used to size storage tanks for external melt ice-on-coil systems.
- Containerized ice storage systems (see Figure 11c). In these systems, small containers of various shape (typically spherical) filled with water are used inside a tank to store energy. The water inside the containers is frozen by directly cooling the solution inside the tank (which acts as the evaporator). The typical volume requirement for containerized ice storage systems is 0.048 m^3/kWh.

Heat Recovery Systems

Heat can be recovered from some HVAC equipment. For instance, heat exchangers can be installed to recover heat from air handling unit (AHU) exhaust air streams and from boiler stacks. Heat recovery technologies such as rotary heat wheels and heat pipes can recover 50% to 80% of the energy used to heat or cool ventilation air supplied to the building.

Desiccant Cooling Systems

Desiccant-based cooling systems are now available and can be used in buildings with large dehumidification loads during long periods (such as hospitals, swimming pools, and supermarket fresh produce areas).

Ground-source Heat Pumps

Geothermal heat pumps can provide an opportunity to take advantage of the heat stored underground to condition building spaces. Some published studies have indicated that ground-coupled heat pumps can save up to 70% of heating and cooling energy (Omer, 2008).

Energy Efficient Motors

The energy cost to operate electric motors can be a significant part of the operating budget of any commercial building. Measures to reduce the energy cost of using motors include reducing operating time (turning off unnecessary equipment), optimizing motor systems, installing controls to match motor output with demand, using variable speed drives for air and water distribution, and installing energy-efficient motors. Figure 9 shows an energy efficient motor with a control panel. Table 3 provides typical efficiencies for several motor sizes. Example 1 illustrates the calculation procedure to estimate the cost-effectiveness of energy-efficient motors.

In addition to the reduction in the total facility electrical energy use, energy efficiency improvements of the electrical systems decrease space cooling loads and therefore further reduce the electrical energy use in the facility.

Cogeneration Systems

This is not really a new technology. However, recent improvements in its combined thermal and electrical efficiency make cogeneration cost effective in

TABLE 3. Typical efficiencies of motors (Krarti, 2000).

Motor Size (hp)	Standard Efficiency	High Efficiency
1	72%	81%
2	76%	84%
3	77%	89%
5	80%	89%
7.5	82%	89%
10	84%	89%
15	86%	90%
20	87%	90%
30	88%	91%
40	89%	92%
50	90%	93%

EXAMPLE 1

Problem: *Consider a 7.5 kW (10-hp) motor that needs to be replaced. There two alternatives for the replacement: either use a standard motor with an energy efficiency of 84% and a cost of $600 or use of high efficiency motor with an energy efficiency of 89% and a cost of $900. Determine the payback period for replacing the exiting motor with the high efficiency motor if the annual operating time is 6,000 hrs and the cost of electricity is $0.08/kWh.*

Solution:
The energy saving in kWh for using the energy efficient motor relative to the standard motor is:

$$\Delta kWh = 7.5 \text{ kW} * \left(\frac{1}{0.84} - \frac{1}{0.89}\right) \cdot 6{,}000 \text{ hrs} = 3{,}000 \text{ kWh/yr}$$

Thus, the simple payback period, SPP, for investing in high efficiency rather than standard motor is:

$$SPP = \frac{(\$900 - \$600)}{3{,}000 \text{ kWh/yr} * \$0.08/\text{kWh}} = 1.25 \text{ yr}$$

several applications including institutional buildings such as hospitals and universities.

Hybrid Cogeneration-HVAC Systems

Hybrid cogeneration-HVAC systems have been considered to reduce the energy use of buildings. A hybrid system can include:

- A variable air volume air handling unit equipped with liquid desiccant to remove moisture from the mixed air.
- A gas-turbine cogeneration system to provide both electricity and heat.

The electricity can be used to serve some of the electrical loads of the building (such as lighting and office equipment). Heat is used to supply hot water to the heating coils and to operate an absorption chiller and a thermal storage system to provide chilled water to the cooling coils. An economic analysis indicates that a hybrid cogeneration-HVAC system can save up to 50% in energy cost of a commercial building (McNeill et al., 2007).

Commissioning of Building Energy Systems

Before final occupancy of a newly constructed building, it is recommended to perform commissioning of its various systems including HVAC systems. Commissioning is a quality assurance process to verify and document the performance of building systems as specified by the design intent. During the commissioning process, operation and maintenance personnel are trained to properly follow procedures that assure that all building systems are fully functional and are properly operated and maintained. For existing facilities, continuous commissioning procedures have been developed and have been implemented in selected buildings with a substantial reduction in energy use.

SUMMARY

In this paper, an outline of selected heating, ventilating, and air-conditioning systems as well as operating strategies have been presented to help designers consider innovative design alternatives for buildings. The outlined description is neither detailed nor comprehensive. It provides, however, a brief overview of some promising technologies that architects and engineers should consider when designing energy efficient buildings.

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