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ASHRAE Research: Improving the Quality of Life

ASHRAE is the world's foremost technical society in the fields of heating, ventilation, air conditioning, and refrigeration. Its members worldwide are individuals who share ideas, identify needs, support research, and write the industry's standards for testing and practice. The result is that engineers are better able to keep indoor environments safe and productive while protecting and preserving the outdoors for generations to come.

One of the ways that ASHRAE supports its members' and industry's need for information is through ASHRAE Research. Thousands of individuals and companies support ASHRAE Research annually, enabling ASHRAE to report new data about material properties and building physics and to promote the application of innovative technologies.

Chapters in the ASHRAE Handbook are updated through the experience of members of ASHRAE Technical Committees and through results of ASHRAE Research reported at ASHRAE conferences and published in ASHRAE special publications, *ASHRAE Transactions*, and ASHRAE's journal of archival research, *Science and Technology for the Built Environment*.

For information about ASHRAE Research or to become a member, contact ASHRAE, 1791 Tullie Circle, Atlanta, GA 30329; telephone: 404-636-8400; www.ashrae.org.

Preface

The 2019 *ASHRAE Handbook—HVAC Applications* comprises 65 chapters covering a broad range of facilities and topics, written to help engineers design and use equipment and systems described in other Handbook volumes. Main sections cover comfort, industrial, energy-related, general applications, and building operations and management. ASHRAE Technical Committees in each subject area have reviewed all chapters and revised them as needed for current technology and design practice.

Full and associate ASHRAE members can download Handbook PDFs in I-P or SI units by going to technologyportal.ashrae.org. Nonmembers can purchase these PDFs at the same location, or purchase individual chapter PDFs from ashrae.org/bookstore.

This edition includes three new chapters:

- Chapter 6, Indoor Swimming Pools
- Chapter 59, Indoor Airflow Modeling
- Chapter 65, Occupant-Centric Sensing and Controls

Other particularly notable highlights include the following:

- Ch 8, Educational Facilities, provides updated design criteria, and a new section on central plant optimization for higher education campuses and educational facilities for students with disabilities.
- Ch. 9, Health Care Facilities, has been extensively rewritten to address current health care requirements.
- Ch. 16, Enclosed Vehicular Facilities, has new material on parking garage ventilation and updated ventilation flow rates.
- Ch. 20, Data Centers and Telecommunication Facilities, includes updates to reflect the current ASHRAE Datacom series, and text updates to reflect changes in the industry and new technologies such as PoE lighting and lithium-ion batteries.
- Ch. 34, Kitchen Ventilation, now discusses solid-fuel cooking, and life-cycle cost analysis, with updates from research and SSPC 154.
- Ch. 35, Geothermal Energy, has new content on direct exchange systems and pressure considerations for deep boreholes, calculation methods for design, and an updated example.
- Ch. 36, Solar Energy, added updated guidance on solar thermal collectors and photovoltaic applications, with new information on design and performance of photovoltaic systems and on installation and operation guidelines for photovoltaic systems, with new practical examples
- Ch. 40, Operation and Maintenance Management, has been extensively rewritten to address current best practices
- Ch. 41, Computer Applications, was extensively rewritten to more directly focus on immediate concerns of HVAC engineers
- Ch. 51, Service Water Heating, added discussion of water heater redundancy in large systems, and has updated information about new uniform energy factor (UEF) ratings, diversified electrical demand of whole-house/large tankless electric water heaters, and a new figure describing recommended tank and plumbing layout for heat pump water heater (HPWH) systems, showing series/parallel arrangement of HPWH and conventional water heaters.
- Ch. 52, Snow Melting, added guidance for recommended values by application type and for concrete strength and maximum temperature difference, as well as discussion of new research.
- Ch. 54, Fire and Smoke Control, has new sections on balanced approach and smoke feedback, plus extensively revised discussion of dampers, pressurization system design, and stairwells with open doors.
- Ch. 60, Integrated Building Design, has been completely rewritten to give more detail on IBD process.
- Ch. 64, Mold and Moisture, revised the order of risk factors for mold to better reflect their relative importance, and added information from ASHRAE research project RP-1712 to advise on components and configuration of dedicated outdoor air (DOAS) systems to help avoid mold growth in schools, universities, and military barracks during extended periods of unoccupied-mode HVAC operation.

This volume is published as a bound print volume and in electronic format as a downloadable PDF and online, in two editions: one using inch-pound (I-P) units of measurement, the other using the International System of Units (SI).

Corrections to the 2016, 2017, and 2018 Handbook volumes can be found on the ASHRAE web site at http://www.ashrae.org and in the Additions and Corrections section of this volume. Corrections for this volume will be listed in subsequent volumes and on the ASHRAE web site.

Reader comments are enthusiastically invited. To suggest improvements for a chapter, **please comment using the form on the ASHRAE web site** or write to Handbook Editor, ASHRAE, 1791 Tullie Circle, Atlanta, GA 30329, or fax 678-539-2187, or e-mail hkennedy@ashrae.org.

Heather E. Kennedy
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CHAPTER 1

RESIDENTIAL SPACE CONDITIONING

SPACE-CONDITIONING systems for residential use vary with both local and application factors. Local factors include energy source availability (present and projected) and price; climate; socioeconomic circumstances; and availability of installation and maintenance skills. Application factors include housing type, construction characteristics, and building codes. As a result, many different systems are selected to provide combinations of heating, cooling, humidification, dehumidification, ventilation, and air filtering. This chapter emphasizes the more common systems for space conditioning of both single-family (i.e., traditional site-built and modular or manufactured homes) and multifamily residences. Low-rise multifamily buildings generally follow single-family practice because constraints favor compact designs; HVAC systems in high-rise apartment, condominium, and dormitory buildings are often of commercial types similar to those used in hotels. Retrofit and remodeling construction also adopt the same systems as those for new construction, but site-specific circumstances may call for unique designs.

1. SYSTEMS

Common residential systems are listed in Table 1. Four generally recognized groups are central forced air, central hydronic, zoned systems, and room or portable equipment. System selection and design involve such key decisions as (1) source(s) of energy, (2) means of distribution and delivery, and (3) terminal device(s).

Climate determines the services needed. Heating and cooling are generally required. Air cleaning, by filtration or electrostatic devices, is present in most systems. Humidification, when used, is provided in heating systems for thermal comfort (as defined in ASHRAE *Standard* 55), health, antiques or art preservation, and reduction of static electricity discharges. Cooling systems usually dehumidify air as well as lowering its temperature. Introduction of outdoor (fresh) air may be required in some applications. Typical forced-air residential installations are shown in Figures 1 and 2.

Table 1 Residential Heating and Cooling Systems

	Central Forced Air	Central Hydronic	Zoned	Room or Portable
Most common energy sources	Gas Oil Electricity	Gas Oil Electricity	Gas Electricity	Electricity
Heat source/ sink	Air Ground Water	Air Water	Air Ground Water	Air
Distribution medium	Air	Water Steam	Air Water Refrigerant	Air
Distribution system	Ducting	Piping	Ducting/dampers Piping or Free delivery	Ducting/free delivery
Terminal devices	Diffusers Registers Grilles	Radiators Radiant panels Fan-coil units	Included with product or same as forced-air or hydronic systems	Diffuser

The preparation of this chapter is assigned to TC 8.11, Unitary and Room Air Conditioners and Heat Pumps.

Figure 1 shows a gas furnace, split-system air conditioner, humidifier, and air filter. Air from the space enters the equipment through a return air duct. It passes initially through the air filter. The circulating blower is an integral part of the furnace, which supplies heat during winter. An optional humidifier adds moisture to the heated air, which is distributed throughout the home via the supply duct. When cooling is required, heat and moisture are removed from the circulating air as it passes across the evaporator coil. Refrigerant lines connect the evaporator coil to a remote condensing unit located outdoors. Condensate from the evaporator is removed through a drain line with a trap.

Figure 2 shows a split-system heat pump, supplemental electric resistance heaters, humidifier, and air filter. The system functions as follows: air from the space enters the equipment through the return air duct (or sometimes through an opening in the equipment itself), and passes through a filter. The circulating blower is an integral part of the indoor air-handling portion of the heat pump system, which supplies heat through the indoor coil during the heating season. Optional electric heaters supplement heat from the heat pump during

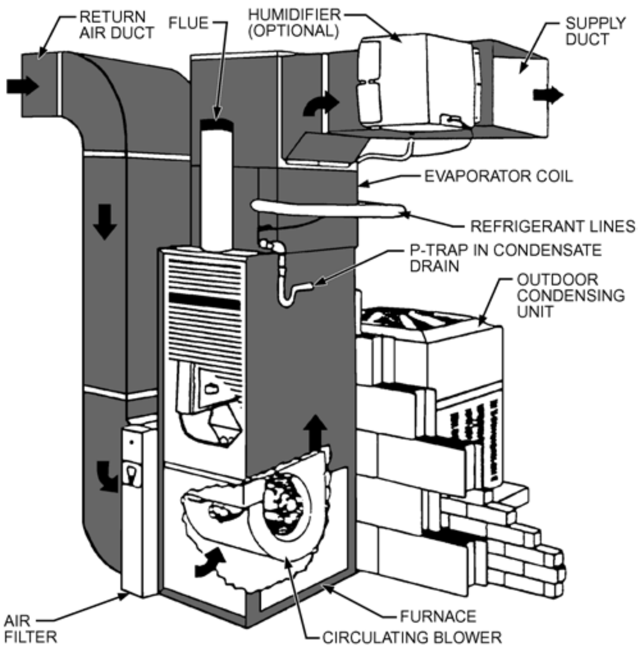

Fig. 1 Typical Residential Installation of Heating, Cooling, Humidifying, and Air Filtering System

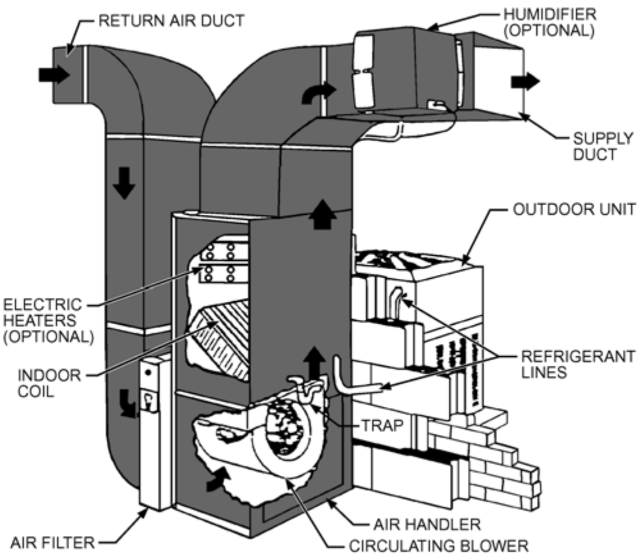

Fig. 2 Typical Residential Installation of a Split-System Air-to-Air Heat Pump

periods of low outdoor temperature and counteract indoor airstream cooling during periodic defrost cycles. This supplemental heat is also referred to as emergency heat since it may function as a backup heat source. Systems referred to as dual fuel apply a furnace to provide some of the functionality of the electric supplemental heat. An optional humidifier adds moisture to the heated air, which is distributed throughout the home through the supply duct. When cooling is required, heat and moisture are removed from the circulating air as it passes across the evaporator coil. Refrigerant lines connect the indoor coil to the outdoor unit. Condensate from the indoor coil is removed through a drain line with a trap.

Minisplit and multisplit systems, which are similar to split systems but are typically ductless, are increasingly popular worldwide. A typical two-zone, ductless multisplit system installation is shown in Figure 3. In this example, the system consists mainly of two sections: an outdoor condensing unit and two indoor air-handling units that are usually installed on perimeter walls of the house. Each indoor air handler serves one zone and is controlled independently from the other indoor unit. Figure 3 shows a top-discharge condensing unit. Side-discharge outdoor units are also widely applied.

Single-package unitary systems, such as window-mounted, through-the-wall, or rooftop units where all equipment is contained in one cabinet, are also popular. Ducted versions are used extensively in regions where residences have duct systems in crawlspaces beneath the main floor and in areas such as the southwestern United States, where rooftop-mounted packages connect to attic duct systems.

Central hydronic heating systems are popular both in Europe and in parts of North America where central cooling has not normally been provided. New construction, especially in multistory homes, now typically includes forced-air cooling.

Zoned systems are designed to condition only part of a home at any one time. Systems may be ducted, duct free, or hydronic. They may consist of individual room units or central systems with zoned distribution networks. Multiple central systems that serve individual floors or the sleeping and common portions of a home separately are sometimes used in large single-family residences.

The energy source is a major consideration in system selection. According to 2015 data from the U.S. Energy Information Administration (EIA 2017), for heating, about 47% of homes use natural

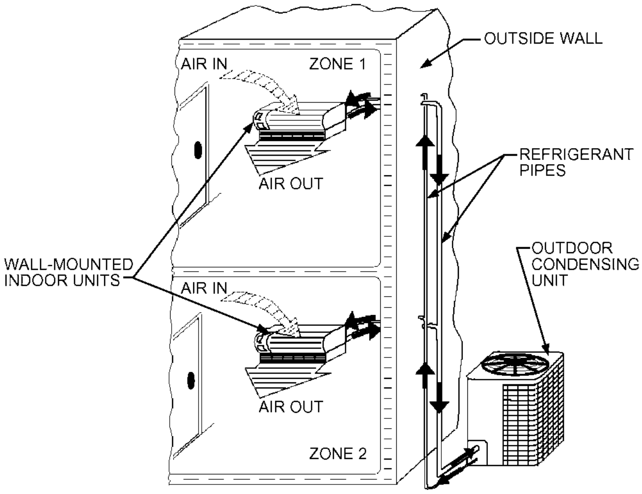

Fig. 3 Example of Two-Zone, Ductless Multisplit System in Typical Residential Installation

gas, followed by electricity (36%), propane (5%), fuel oil/kerosene (5%), and wood (2%). Relative prices, safety, and environmental concerns (both indoor and outdoor) are further factors in heating energy source selection. Where various sources are available, economics strongly influence the selection. Electricity is the dominant energy source for cooling.

2. EQUIPMENT SIZING

The heat loss and gain of each conditioned room and of ductwork or piping run through unconditioned spaces in the structure must be accurately calculated to select equipment with the proper heating and cooling capacity. To determine heat loss and gain accurately, the floor plan and construction details, including information on wall, ceiling, and floor construction as well as the type and thickness of insulation, must be known. Window design and exterior door details are also needed. With this information, heat loss and gain can be calculated using the Air-Conditioning Contractors of America (ACCA) *Manual* J® or similar calculation procedures. From there, equipment selections can be made using ACCA *Manual* S® or other equipment selection procedures. To conserve energy, many jurisdictions require that the building be designed to meet or exceed the requirements of ASHRAE *Standard* 90.2 or similar requirements.

Proper matching of equipment capacity to the building heat loss and gain is essential. Building loads vary throughout the day and across seasons, so matching capacity to load can be a challenge. Variable and multistage equipment have a wide capacity range, so oversizing is less of an issue. The heating capacity of air-source heat pumps is usually supplemented by auxiliary heaters, most often of the electric resistance type; in some cases, however, fossil fuel furnaces or solar systems are used.

Undersized equipment will be unable to maintain the intended indoor temperature under extreme outdoor temperatures. Some oversizing may be desirable to enable recovery from setback and to maintain indoor comfort during outdoor conditions that are more extreme than the nominal design conditions. Grossly oversized equipment can cause discomfort because of short *on*-times, wide indoor temperature swings, and inadequate dehumidification when cooling. Gross oversizing may also contribute to higher energy use by increasing cyclic losses. Excessive cycling is also a reliability concern. Variable-capacity equipment (heat pumps, air conditioners, and furnaces) can more closely match building loads over broad ambient temperature ranges, usually reducing these losses and improving comfort levels; in the case of heat pumps, supplemental heat needs may also be reduced.

Residences of tight construction may have high indoor humidity and a build-up of indoor air contaminants at times. Air-to-air heat recovery equipment may be used to provide tempered ventilation air to tightly constructed houses. See Chapter 26 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* for additional information on air-to-air heat recovery. Outdoor air intakes connected to the return duct of central systems may also be used when reducing installed costs is important. Simple exhaust systems with or without passive air intakes are also popular. Natural ventilation by operable windows is also popular in some climates. Excessive accumulation of radon is of concern in all buildings; lower-level spaces should not be depressurized, which causes increased migration of soil gases into buildings. All ventilation schemes increase heating and cooling loads and thus the required system capacity, thereby resulting in greater energy consumption. In all cases, minimum ventilation rates, as described in ASHRAE *Standards* 62.1 and 62.2, as applicable, should be maintained.

3. SINGLE-FAMILY RESIDENCES

Furnaces

Furnaces are fueled either by electricity, or by combustible materials; gas (natural or propane), oil, and wood are most common. Electric furnaces are comprised of electric resistance heaters and a blower fan.

Combustion furnaces may draw combustion air from inside the house or from outdoors. If the furnace space is located such that combustion air is drawn from the outdoors, the arrangement is called an **isolated combustion system (ICS)**. Furnaces are generally rated on an ICS basis. Outdoor air is ducted to the combustion chamber (a direct-vent system) for manufactured home applications and some mid- and high-efficiency equipment designs. Using outdoor air for combustion eliminates both infiltration losses associated with using indoor air for combustion and stack losses associated with atmospherically induced draft-hood-equipped furnaces.

Two available types of high-efficiency gas furnaces are noncondensing and condensing. Both increase efficiency by adding or improving heat exchanger surface area and reducing heat loss during furnace off times. Noncondensing furnaces usually have combustion efficiencies below 85%, and condensing furnaces have combustion efficiencies higher than 90%. The higher-efficiency condensing type recovers more energy by condensing water vapor from combustion products. Condensate is formed in a corrosion-resistant heat exchanger and is disposed of through a drain line. Care must be taken to prevent freezing the condensate when the furnace is installed in an unheated space such as an attic. Noncondensing furnaces use metallic vents, whereas condensing furnaces generally use PVC for vent pipes and condensate drains.

Chapters 31 and 33 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* include more detailed information on furnaces and furnace efficiency.

Hydronic Heating Systems

With the growth of demand for central cooling systems, hydronic systems have declined in popularity in new construction, but still account for a significant portion of existing systems in colder climates. The fluid is heated in a central boiler and distributed by piping to terminal units in each room. Terminal units are typically either radiators or baseboard convectors. Other terminal units include fan-coils and radiant panels. Most recently installed residential systems use a forced-circulation, multiple-zone hot-water system with a series-loop piping arrangement. Chapters 13 and 36 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* have more information on hydronics, and Chapter 32 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* provides more information on boilers.

Design water temperature is based on economic and comfort considerations. Generally, higher temperatures result in lower first costs because smaller terminal units are needed. However, losses tend to be greater, resulting in higher operating costs and reduced comfort because of the concentrated heat source. Typical design temperatures for radiator systems range from 80 to 95°C. For radiant panel systems, design temperatures range from 45 to 75°C. The preferred control method allows the water temperature to decrease as outdoor temperatures rise. Provisions for expansion and contraction of piping and heat distributing units and for eliminating air from the hydronic system are essential for quiet, leak-tight operation.

Fossil fuel systems that condense water vapor from the flue gases must be designed for return water temperatures in the range of 50 to 55°C for most of the heating season. Noncondensing systems must maintain high enough water temperatures in the boiler to prevent this condensation. If rapid heating is required, both terminal unit and boiler size must be increased, although gross oversizing should be avoided.

Another concept for multi- or single-family dwellings is a combined water-heating/space-heating system that uses water from the domestic hot-water storage tank to provide space heating. Water circulates from the storage tank to a hydronic coil in the system air handler. Space heating is provided by circulating indoor air across the coil. A split-system central air conditioner with the evaporator located in the system air handler can be included to provide space cooling.

Solar Heating

Both active and passive solar thermal energy systems are sometimes used to heat residences. In typical active systems, flat-plate collectors heat air or water. Air systems distribute heated air either to the living space for immediate use or to a thermal storage medium (e.g., a rock pile). Water systems pass heated water from the collectors through a heat exchanger and store heat in a water tank. Because of low delivered-water temperatures, radiant floor panels requiring moderate temperatures are often used. A water-source heat pump between the water storage tank and the load can be used to increase temperature differentials.

Trombe walls, direct-gain, and greenhouse-like sunspaces are common passive solar thermal systems. Glazing facing south (in the northern hemisphere), with overhangs to reduce solar gains in the summer, and movable night insulation panels reduce heating requirements.

Some form of back-up heating is generally needed with solar thermal energy systems. Solar electric systems are not normally used for space heating because of the high energy densities required and the economics of photovoltaics. However, hybrid collectors, which combine electric and thermal capabilities, are available. Chapter 37 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* has information on sizing solar heating equipment.

Heat Pumps

Heat pumps for single-family houses are normally centrally ducted unitary or duct-free unitary split systems, as shown in Figures 2 and 3.

Most commercially available heat pumps, particularly in North America, are reversible, electrically powered, air-source systems. The direction of flow of the refrigerant can be switched to provide cooling or heating to the home.

Heat pumps may be classified by thermal source and distribution medium in the heating mode as well as the type of fuel used. The most common classifications of heat pump equipment are air-to-air and water-to-air. Air-to-water and water-to-water types are also used.

Heat pump systems are generally described as air-source or ground-source. The thermal sink for cooling is generally assumed to be the same as the thermal source for heating.

Air-Source Systems. Air-source systems using ambient air as the heat source/sink can be installed in almost any application and are generally the least costly to install and thus the most commonly used.

Ground-Source (Geothermal) Systems. Ground-source systems usually use water-to-air heat pumps to extract heat from the ground using groundwater or a buried heat exchanger. As a heat source/sink, groundwater (from individual wells or supplied as a utility from community wells) offers the following advantages over ambient air: (1) heat pump capacity is independent of ambient air temperature, reducing supplemental heating requirements; (2) no defrost cycle is required; (3) although operating conditions for establishing rated efficiency are not the same as for air-source systems, seasonal efficiency is usually higher for heating and for cooling; and (4) peak heating energy consumption is usually lower.

Two other system types are ground-coupled and surface-water-coupled systems. **Ground-coupled systems** offer the same advantages, but because surface water temperatures track fluctuations in air temperature, **surface-water-coupled systems** may not offer the same benefits as other ground-source systems. Both system types circulate brine or water in a buried or submerged heat exchanger to transfer heat from the ground or water. **Direct-expansion ground-source systems**, with evaporators buried in the ground, also are available but are seldom used. **Water-source systems** that extract heat from surface water (e.g., lakes or rivers) or city (tap) water are sometimes used where local conditions allow. See Chapter 49 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* for further information.

Water supply, quality, and disposal must be considered for groundwater systems. Caneta Research (1995) and Kavanaugh and Rafferty (2014) provide detailed information on these subjects. Secondary coolants for ground-coupled systems are discussed in Caneta Research (1995) and in Chapter 31 of the 2017 *ASHRAE Handbook—Fundamentals*. Buried heat exchanger configurations may be horizontal or vertical, with the vertical including both multiple-shallow- and single-deep-well configurations. Ground-coupled systems avoid water quality, quantity, and disposal concerns but are sometimes more expensive than groundwater systems. However, ground-coupled systems are usually more efficient, especially when pumping power for the groundwater system is considered. Proper installation of the ground coil(s) is critical to success.

Hybrid or Dual-Fuel Systems. In add-on systems, typically called dual-fuel or hybrid, a heat pump is added (often as a retrofit) to an existing furnace or boiler/fan-coil system. The heat pump and combustion device are operated in one of two ways: (1) alternately, depending on which is most cost-effective, or (2) in parallel. Bivalent heat pumps, factory-built with the heat pump and combustion device grouped in a common chassis and cabinets, provide similar benefits at lower installation costs.

Fuel-Fired Heat Pumps. Fuel-fired heat pumps for residential applications are available in North America and Europe. Usually, these systems take the form of absorption cycles. For results of one investigation on these heat pumps, see Grossman et al. (1995).

Water-Heating Options. Heat pumps may be equipped with desuperheaters (either integral or field-installed) to reclaim heat for domestic water heating when operated in cooling mode. Integrated space-conditioning and water-heating heat pumps with an additional full-size condenser for water heating are also available. ASHRAE *Standard* 124 provides a method of test for rating combination space- and water-heating appliances.

Zoned Heating and Cooling Systems

Most moderate-cost residences in North America have single-thermal-zone HVAC systems with one thermostat. Multizoned systems, however, offer the potential for improved thermal comfort. Lower operating costs are possible with zoned systems because unoccupied areas (e.g., common areas at night, sleeping areas during the day) can be kept at lower temperatures in the winter.

One form of this system consists of individual equipment located in each room. Room heaters are usually electric or gas-fired. Electric heaters are available in the following types: baseboard free-convection, wall insert (free-convection or forced-fan), radiant panels for walls and ceilings, and radiant cables for walls, ceilings, and floors. Matching equipment capacity to heating requirements is critical for individual room systems. Heating delivery cannot be adjusted by adjusting air or water flow, so greater precision in room-by-room sizing is needed. Most individual heaters have integral thermostats that limit the ability to optimize unit control without continuous fan operation.

Room air conditioners are typically electrically operated. Window, room, and packaged terminal air conditioners (PTACs) provide both sensible and latent cooling. Window air conditioners are inexpensive and simple to install where a central system does not exist or does not provide sufficient comfort in one room or zone. Room air conditioners are similar to window air conditioners, except the condenser typically pulls air from the indoors rather than outdoors, and the appliance is floor standing with ducts to a small window-mounted panel to reject condenser heat to the outdoors. PTACs are designed to mount in a framed wall opening, so are a permanent rather than seasonal addition to a building. Some PTACs are heat pumps, so can provide both heating and cooling. In dry climates, direct-evaporative coolers ("swamp coolers") can improve comfort, and room humidifiers or dehumidifiers can be used in any climate. Ceiling and portable fans are also widely used to improve comfort within a room. Each of these room appliances typically has its own dedicated sensors and controls in the same room. Some new room equipment can be connected to the Internet, enabling coordination of service across the whole house.

Individual heat pumps for each room or group of rooms (zone) are another form of zoned electric heating. For example, two or more small unitary heat pumps can be installed in two-story or large one-story homes.

The multisplit heat pump consists of a central compressor and an outdoor heat exchanger to serve multiple indoor zones. Each zone uses one or more fan-coils, with separate thermostatic controls for each zone. These systems are used in both new and retrofit construction. These are also known as **variable-refrigerant-volume (VRV)** or **variable-refrigerant-flow (VRF) systems**, and may include a heat recovery mode where some indoor units operate in heating and some in cooling simultaneously. For more information on VRF systems, see Chapter 18 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*.

A method for zoned heating and cooling in central ducted systems is the zone-damper system. This consists of individual zone dampers and thermostats combined with a zone control system. Both variable-air-volume (damper position proportional to zone demand) and on/off (damper fully open or fully closed in response to thermostat) types are available. These systems sometimes include a provision to modulate to lower capacities when only a few zones require conditioning. Because weather is the primary influence on the load, the cooling or heating load in each room changes from hour to hour. Therefore, the owner or occupant should be able to make seasonal or more frequent adjustments to the air distribution system to improve comfort. Adjustments may involve opening additional outlets in second-floor rooms during summer and throttling or closing heating outlets in some rooms during winter. Manually adjustable balancing dampers may be provided to facilitate these adjustments. Other possible refinements are installing a heating and cooling system sized to meet heating requirements, with additional self-contained cooling units serving rooms with high summer loads, or separate central systems for the upper and lower floors of a house. Alternatively, zone-damper systems can be used. Another way of balancing cooling and heating loads is to use variable-capacity compressors in heat pump systems.

Operating characteristics of both heating and cooling equipment must be considered when zoning is used. For example, reducing air quantity to one or more rooms may reduce airflow across the evaporator to such a degree that frost forms on the fins. Reduced airflow on heat pumps during the heating season can cause overloading if airflow across the indoor coil is not maintained above 45 L/s per kilowatt. Reduced air volume to a given room reduces the air velocity from the supply outlet and might cause unsatisfactory air distribution in the room. Manufacturers of zoned systems normally provide guidelines for avoiding such situations. Some hydronic systems use valve manifolds near the boiler to provide hydronic heat on a zonal basis. Each room's radiator or convector is served by dedicated piping from the valve manifold, with a common return pipe. The variable valves are all independently controlled by room thermostats, based on thermal demand.

Unitary Air Conditioners

In forced-air systems, the same air distribution duct system can be used for both heating and cooling. Split-system central cooling, as shown in Figure 1, is the most widely used forced-air system. Upflow, downflow, and horizontal-airflow indoor units are available. Condensing units are installed on a noncombustible pad outdoor and contain a motor- or engine-driven compressor, condenser, condenser fan and fan motor, and controls. The condensing unit and evaporator coil are connected by refrigerant tubing that is normally field-supplied. However, precharged, factory-supplied tubing with quick-connect couplings is also common where the distance between components is not excessive.

A distinct advantage of split-system central cooling is that it can readily be added to existing forced-air heating systems. Airflow rates are generally set by the cooling requirements to achieve good performance, but most existing heating duct systems are adaptable to cooling. Airflow rates of 45 to 60 L/s per kilowatt of refrigeration are normally recommended for good cooling performance. Specialty systems such as small-duct high-velocity (SDHV) systems have lower airflows and are used in applications where retrofitting larger supply ducts is not possible. As with heat pumps, split-system central cooling may be fitted with desuperheaters for domestic water heating.

Some cooling equipment includes forced-air heating as an integral part of the product. Year-round heating and cooling packages with a gas, oil, or electric furnace for heating and a vapor-compression system for cooling are available. Air-to-air and water-source heat pumps provide cooling and heating by reversing the flow of refrigerant.

Distribution. Duct systems for cooling (and heating) should be designed and installed in accordance with accepted practice. Useful information is found in ACCA *Manuals* D® and S®.

There is renewed interest in quality duct design, because it can make a large difference in the effectiveness of the residential unitary cooling and heating system. There is a trend toward placing as much ductwork as possible in the conditioned space, to reduce duct thermal losses and lessen the effect of any leaks that exist. For a given diameter, flexible ducts have higher pressure drop than metal ducts, and this should be taken into consideration. Flexible duct must be stretched and properly supported or it can sag, increasing airflow resistance. Minimizing duct system airflow resistance helps minimize energy consumption throughout the life of the system.

Chapter 21 of the 2017 *ASHRAE Handbook—Fundamentals* provides the theory behind duct design. In the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 10 discusses air distribution design for small heating and cooling systems, Chapter 19 addresses duct construction and code requirements, and Chapter 49 provides more detailed information on unitary air conditioners and heat pumps.

Special Considerations. In residences with more than one story, cooling and heating are complicated by air buoyancy, also known as the **stack effect**. In many such houses, especially with single-zone systems, the upper level tends to overheat in winter and undercool in summer. Multiple air outlets, some near the floor and others near the ceiling, have been used with some success on all levels. To control airflow, the homeowner opens some outlets and closes others from season to season. Free air circulation between floors can be reduced by locating returns high in each room and keeping doors closed.

In existing homes, the cooling that can be added is limited by the air-handling capacity of the existing duct system. Although the existing duct system size is usually satisfactory for normal occupancy, it may be inadequate during large gatherings. When new cooling (or heating) equipment is installed in existing homes, supply air ducts and outlets should be checked for acceptable air-handling capacity and air distribution. Maintaining upward airflow at an effective velocity is important when converting existing heating systems with floor or baseboard outlets to both heat and cool. It is not necessary to change the deflection from summer to winter for registers located at the perimeter of a residence. Registers located near the floor on the indoor walls of rooms may operate unsatisfactorily if the deflection is not changed from summer to winter.

A residence without a forced-air heating system may be cooled by one or more central systems with separate duct systems, by individual room air conditioners (window-mounted or through-the-wall), or by minisplit room air conditioners.

Cooling equipment must be located carefully. Because cooling systems require higher indoor airflow rates than most heating systems, sound levels generated indoors are usually higher. Thus, indoor air-handling units located near sleeping areas may require sound attenuation. Outdoor noise levels should also be considered when locating the equipment. Many communities have ordinances regulating the sound level of mechanical devices, including cooling equipment. Manufacturers of unitary air conditioners often rate the sound level of their products according to an industry standard (Air-Conditioning, Heating, and Refrigeration Institute [AHRI] *Standard* 270). AHRI *Standard* 275 gives information on how to predict the sound level in dBA when the AHRI sound rating number, the equipment location relative to reflective surfaces, and the distance to the property line are known.

An effective and inexpensive way to reduce noise is to put distance and natural barriers between sound source and listener. However, airflow to and from air-cooled condensing units must not be obstructed; for example, plantings and screens must be porous and placed away from units so as not to restrict intake or discharge of air. Most manufacturers provide recommendations on acceptable distances between condensing units and natural barriers. Outdoor units should be placed as far as is practical from porches and patios, which may be used while the house is being cooled. Locations near bedroom windows and occupied spaces of neighboring homes should also be avoided. In high-crime areas, consider placing units on roofs or other semisecure areas.

Evaporative Coolers

In climates that are dry throughout the entire cooling season, evaporative coolers can be used to cool residences. They must be installed and maintained carefully to reduce the potential for water and thus air quality problems. Further details on evaporative coolers can be found in Chapter 41 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* and in Chapter 52 of this volume.

Humidifiers

For improved winter comfort, equipment that increases indoor relative humidity may be needed. In a ducted heating system, a central whole-house humidifier can be attached to or installed within a supply plenum or main supply duct, or installed between the supply and return duct systems. When applying supply-to-return duct humidifiers on heat pump systems, take care to maintain proper airflow across the indoor coil. Self-contained portable or tabletop humidifiers can be used in any residence. Even though this type of humidifier introduces all the moisture to one area of the home, moisture migrates and raises humidity levels in other rooms.

Overhumidification should be avoided: it can cause condensate to form on the coldest surfaces in the living space (usually windows). Also, because moisture migrates through all structural materials, vapor retarders should be installed near the warmer indoor surface of insulated walls, ceilings, and floors in most temperature climates. Lack of attention to this construction detail allows moisture to migrate from indoors to outdoors, causing damp insulation, mold, possible structural damage, and exterior paint blistering. Chapters 25 to 27 of the 2017 *ASHRAE Handbook—Fundamentals* provide further details.

Central humidifiers may be rated in accordance with AHRI *Standard* 611. This rating is expressed in the number of litres per day evaporated by 49°C entering air. Selecting the proper size humidifier is important and is outlined in AHRI *Guideline* F.

Humidifier cleaning and maintenance schedules must be followed to maintain efficient operation and prevent bacteria build-up.

Chapter 22 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* contains more information on residential humidifiers.

Dehumidifiers

Many homes also use dehumidifiers to remove moisture and control indoor humidity levels. In cold climates, dehumidification is sometimes required during the summer in basement areas to control mold and mildew growth and to reduce zone humidity levels. Traditionally, portable dehumidifiers have been used to control humidity in this application. Although these portable units are not always as efficient as central systems, their low first cost and ability to serve a single zone make them appropriate in many circumstances.

In hot, humid climates, providing sufficient dehumidification with sensible cooling is important. Although conventional air-conditioning units provide some dehumidification as a consequence of sensible cooling, in some cases space humidity levels can still exceed comfortable levels. Residential dehumidifiers almost exclusively rely on direct-expansion refrigeration systems, operating with evaporator temperatures below the process air's dew point, to dehumidify the air through condensation.

Several dehumidification enhancements to conventional air-conditioning systems are possible to improve moisture removal characteristics and lower the space humidity level. Some simple improvements include lowering the supply airflow rate to overcool the airstream, and eliminating off-cycle fan operation. Additional equipment options such as condenser/reheat coils, sensible-heat-exchanger-assisted evaporators (e.g., heat pipes), and subcooling/reheat coils can further improve dehumidification performance. Desiccants, applied as either thermally activated units or heat recovery systems (e.g., enthalpy wheels), can also increase dehumidification capacity and lower the indoor humidity level. Some dehumidification options add heat to the conditioned zone that, in some cases, increases the load on the sensible cooling equipment. Dehumidifiers are rated in accordance with Association of Home Appliance Manufacturers (AHAM) *Standard* DH-1. Chapter 25 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* contains more information on residential dehumidifiers.

Air Filters

Most comfort conditioning systems that circulate air incorporate some form of air filter. Usually, they are disposable or cleanable filters that have relatively low air-cleaning efficiency. Alternatives with higher air-cleaning efficiencies include pleated media filters and electronic air filters. These filters may have higher static pressure drops. The air distribution system should be carefully evaluated before installing such filters so that airflow rates are not overly reduced with their use. Airflow must be evaluated both when the filter is new and when it is in need of replacement or cleaning.

Air filters are mounted in the return air duct or plenum and operate whenever air circulates through the duct system. Air filters are rated in accordance with AHRI *Standard* 681, which was based on ASHRAE *Standard* 52.2. Atmospheric dust spot efficiency levels are generally less than 20% for disposable filters and vary from 60 to 90% for electronic air filters. However, increasingly, the minimum efficiency rating value (MERV) from ASHRAE *Standard* 52.2 is given instead; a higher MERV implies greater particulate removal, but also typically increased air pressure drop for the same filter depth.

To maintain optimum performance, the collector cells of electronic air filters must be cleaned periodically. Automatic indicators are often used to signal the need for cleaning. Electronic air filters have higher initial costs than disposable or pleated filters, but generally last the life of the air-conditioning system. Also available are gas-phase filters such as those that use activated carbon. Chapter 29 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* covers the design of residential air filters in more detail.

Ultraviolet (UV) germicidal light as an air filtration system for residential applications has become popular recently. UV light has been successfully used in health care facilities, food-processing plants, schools, and laboratories. It can break organic molecular bonds, which translates into cellular or genetic damages for microorganisms. Single or multiple UV lamps are usually installed in the return duct or downstream of indoor coils in the supply duct. Direct exposure of occupants to UV light is avoided because UV light does not pass through metal, glass, or plastic. This air purification method effectively reduces the transmission of airborne germs, bacteria, molds, viruses, and fungi in the airstreams without increasing duct pressure losses. The power required by each UV lamp might range between 30 and 100 W, depending on the intensity and exposure time required to kill the various microorganisms. Chapter 17 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* and Chapter 60 of this volume cover the design and application of UV lamp systems in more detail.

Ventilation

Historically, residential buildings have not required active mechanical ventilation. They were built without focus on airtightness, so in general natural infiltration along with some use of spot ventilation was sufficient to maintain indoor air quality at a safe and comfortable level. Because recent construction codes have increased energy efficiency, mechanical ventilation is generally necessary for energy-efficient housing. ASHRAE *Standard* 62.2 provides guidance on selecting ventilation airflow rates, based on the method used for distributing that air throughout the home. Chapter 16 of the 2017 *ASHRAE Handbook—Fundamentals* provides additional information on residential ventilation.

Controls

Residential heating and cooling equipment is controlled by one or more thermostats, which call for heating and cooling from the equipment's embedded control board, and a zone control system if installed. A useful guideline is to install thermostats on an interior wall in a frequently occupied area, about 1.5 m from the floor and away from exterior walls and registers to avoid unintended short-cycling of the equipment when cold or hot air blows on the thermostat. A typical simple wall thermostat contains a temperature sensor and microelectronics that request the heating and cooling equipment operate when the measured temperature falls outside of a dead band, typically ±0.56 K centered at the owner's desired set point.

Programmable thermostats can set heating and cooling equipment at different temperature levels, depending on the time of day or week. This has led to night setback, workday, and vacation control to reduce energy demand and operating costs. For heat pump equipment, electronic thermostats can incorporate night setback with an appropriate scheme to limit use of resistance heat during recovery. Several manufacturers offer thermostats that measure and display relative humidity and actively change the evaporator blower speed to improve latent cooling during times of high humidity.

Modern thermostats use additional sensors, such as remote room temperature, humidity, and motion sensors, or integrate with external computing platforms (e.g., mobile phones) to monitor occupants' locations and enable automatic return when people enter a geographic radius from the home. The use of machine learning, geofencing, and other emerging features is very promising for reducing energy consumption and costs while maintaining or improving user comfort. These so-called **smart thermostats** can be integrated with both noncommunicating and communicating HVAC systems. Some communicating systems require a smart thermostat, often by the same manufacturer, to take advantage of the improved efficiency and fault detection/diagnostic features that a communicating HVAC system provides. For example, most minisplit heat pumps are accompanied by a remote controller that contains the system thermostat, a display, and other user controls. Chapter 47 contains more details about automatic control systems.

In traditional (noncommunicating) systems, the thermostat uses relay logic, or discrete on/off voltage signals, to control the operation of the HVAC system. This results in having to run many wires from the thermostat to the indoor unit and outdoor unit. Some residential systems require 12 wires to be connected and therefore have high risk of being miswired during installation.

A communicating system replaces the many wires with serial communications over two, three, or four wires only, as depicted in Figure 4. In a communicating HVAC system, the indoor unit, outdoor unit, and thermostat act as nodes on a network that send and receive messages to and from each other across a limited number of wires. Each node (device) has its own unique electronic address. Messages are packaged into a common format called a communications protocol and transported to their destinations on the network. In retrofits, these systems offer the ease of plug-and-play installation using existing wiring. A homeowner can replace an existing single-stage furnace and air conditioner with two-stage or variable-capacity equipment and not need to run additional wires. In theory, communications between nodes could also be wireless if they were equipped with radio transceivers.

Communicating systems are a relatively recent addition to residential HVAC, having shown their usefulness in commercial HVAC. The advent of electronics to control the evaporator coil (by modulating both the electronic expansion valve and the blower) and the condensing unit (primarily through monitoring and modulating the compressor) enable systems to take advantage of communications. Communicating systems are easier to install than noncommunicating systems and offer more options to the HVAC engineer.

Communicating HVAC systems also allow an advanced level of system diagnostics. Because nodes communicate in messages, not signals, unlimited amounts of information could be transferred across the few wires of a communicating system. Messages could convey commands or just carry information. This contrasts with having to add a new wire for each additional (analog) signal, as is the case of noncommunicating systems. For example, in a communicating system, the outdoor unit could announce that it has a variable-capacity compressor and the thermostat could command the compressor to turn on and to ramp to a certain speed. The thermostat could ask the outdoor unit for the measured ambient temperature to display it on its screen, or the outdoor unit could send a message to the thermostat to alert the homeowner that a pressure switch is open.

For an HVAC system to be communicating, each device (node) must have an electronic circuit board with a microprocessor. The board gets data from sensors and other HVAC components that are connected to it (e.g., compressor contactor, pressure switches, reversing valve, blower fan, indoor electric heater). The microprocessor packages the data collected from those components into messages and sends them to other nodes on the network. The microprocessor of each node also receives messages from other nodes intended for that node. Although many new residential HVAC systems have some electronics in them, to be considered communicating, the microprocessor must be able to handle the additional burden of implementing the communications protocol as well as handling the traffic of messages on the network. Currently, all communicating systems use proprietary protocols and do not allow matching indoor and outdoor equipment using different protocols.

Networking the components of a residential HVAC system to form a communicating system provides a framework for sharing information within the network as well as with external devices. A wired or wireless gateway, either stand-alone or integrated into any of the communicating nodes, is often used to facilitate data transfer. This enables the HVAC system to be remotely

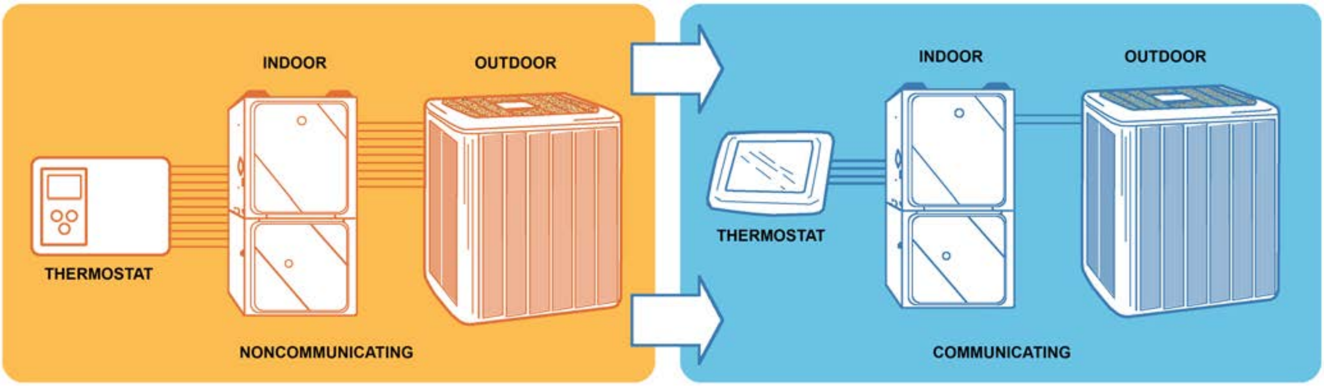

Fig. 4 Communicating HVAC Systems Simplify Wiring

accessible to networked devices such as smart phones, laptops, mobile devices, the electric utility company's smart meter, or cloud services. This remote accessibility, together with the wealth of system information available in a communicating system, allows innovations in the way HVAC systems are maintained and managed. For example, a homeowner could monitor the sensed temperature at the thermostat, check/set the thermostat set-point temperature, change thermostat schedules, and receive maintenance notifications using a smart phone. Electric utilities can supply a signal to reduce electrical demand, and the communicating control system can acknowledge and act on this signal.

4. MULTIFAMILY RESIDENCES

Attached homes and low-rise multifamily apartments generally use heating and cooling equipment comparable to applications used in single-family dwellings. Separate systems for each unit allow individual control to suit the occupant and facilitate individual metering of energy use; separate metering and direct billing of occupants encourages energy conservation.

Forced-Air Systems

High-rise multifamily structures may use unitary, minisplit, or multisplit heating or cooling equipment similar to applications in single-family dwellings. Equipment may be installed in a separate mechanical equipment room in the apartment, on a balcony, or above a dropped ceiling over a hallway or closet. Split system (condensing or heat pump) outdoor units are often placed on roofs, balconies, or the ground. Other common applications include through-the-wall or wall-mounted systems.

Small residential warm-air furnaces may also be used, but a means of providing combustion air and venting combustion products from gas- or oil-fired furnaces is required. It may be necessary to use a multiple-vent chimney or a manifold-type vent system. Local codes must be consulted. Direct-vent furnaces that are placed near or on an outer wall are also available for apartments.

Hydronic Systems

Individual heating and cooling units are not always possible or practical in high-rise structures. In this case, applied central systems are used. Two- or four-pipe hydronic central systems are widely used in high-rise apartments. Each dwelling unit has either individual room units or ducted fan-coil units.

An on-demand water heater may also be used as a source of heat for the hydronic coil instead of a central system. In these applications, the on-demand water heater serves as a source of heat and hot water for the individual apartment. Cooling may come from a central hydronic system, window air conditioner, or typical unitary condenser, as described in the section on Forced-Air Systems.

The most flexible hydronic system with usually the lowest operating costs is the four-pipe type, which provides heating or cooling for each apartment dweller. The two-pipe system is less flexible because it cannot provide heating and cooling simultaneously. This limitation causes problems during the spring and fall when some apartments in a complex require heating while others require cooling because of solar or internal loads. This spring/fall problem may be overcome by operating the two-pipe system in a cooling mode and providing the relatively low amount of heating that may be required by means of individual electric resistance heaters.

See the section on Hydronic Heating Systems for description of a combined water-heating/space-heating system for multi- or single-family dwellings. Chapter 13 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* discusses hydronic design in more detail.

Through-the-Wall Units

Through-the-wall room air conditioners, packaged terminal air conditioners (PTACs), packaged terminal heat pumps (PTHPs), single-package vertical air conditioners (SPVACs), and single-package vertical heat pumps (SPVHPs) can be used for conditioning single rooms. Each room with an outer wall may have such a unit. These units are used extensively in renovating old buildings because they are self-contained and typically do not require complex piping or ductwork renovation.

Room air conditioners have integral controls and may include resistance or heat pump heating. PTACs and PTHPs have special indoor and outdoor appearance treatments, making them adaptable to a wider range of architectural needs. PTACs can include gas, electric resistance, hot water, or steam heat. Integral or remote wall-mounted controls are used for both PTACs and PTHPs. Further information may be found in Chapter 50 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* and in AHRI *Standard* 310/380.

Water-Loop Heat Pumps

Any mid- or high-rise structure having interior zones with high internal heat gains that require year-round cooling can efficiently use a water-loop heat pump. Such systems have the flexibility and control of a four-pipe system but use only two pipes. Water-source heat pumps allow individual metering of each apartment. The building owner pays only the utility cost for the circulating pump, cooling tower, and supplemental boiler heat. Existing buildings can be retrofitted with heat flow meters and timers on fan motors for individual metering.

In some applications, the ground can be used as a heat sink with a geothermal heat pump. This type of application can be advantageous in areas where the water table is high and the soil is porous.

Special Concerns for Apartment Buildings

Many ventilation systems are used in apartment buildings. Local building codes generally govern outdoor air quantities. ASHRAE *Standard* 62.2 provides guidance on selecting ventilation airflow rates based on the method used for distributing that air throughout the building. Chapter 16 of the 2017 *ASHRAE Handbook—Fundamentals* provides additional information on residential ventilation.

Buildings using exhaust and supply air systems may benefit from air-to-air heat or energy recovery devices (see Chapter 26 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*). Such recovery devices can reduce energy consumption by transferring 40 to 80% of the sensible heat and some equipment latent heat between the exhaust air and supply airstreams. In some buildings with centrally controlled exhaust and supply systems, the systems are operated on time clocks for certain periods of the day. In other cases, the outdoor air is reduced or shut off during extremely cold periods. If known, these factors should be considered when estimating heating and cooling loads.

Frequently, long line lengths and elevation changes may be required. For these situations, refrigerant piping must be designed to meet requirements on refrigerant charge migration, pressure drop, and oil return to the compressor. For further information, see Chapter 49 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment.*

Another important load, frequently overlooked, is heat gain from piping for hot-water services.

Infiltration loads in high-rise buildings without ventilation openings for perimeter units are not controllable year-round by general building pressurization. When outer walls are penetrated to supply outdoor air to unitary or fan-coil equipment, combined wind and thermal stack effects create other infiltration problems.

Interior public corridors in apartment buildings need conditioning and smoke management to meet their ventilation and thermal needs, and to meet the requirements of fire and life safety codes. Stair towers, however, are normally kept separate from hallways to maintain fire-safe egress routes and, if needed, to serve as safe havens until rescue. Therefore, great care is needed when designing buildings with interior hallways and stair towers. Chapter 53 provides further information.

Air-conditioning equipment must be isolated to reduce noise generation or transmission. The design and location of cooling towers must be chosen to avoid disturbing occupants within the building and neighbors in adjacent buildings. Also, for cooling towers, prevention of *Legionella* is a serious concern. Further information on cooling towers is in Chapter 40 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*.

In large apartment houses, a central building energy management system may allow individual apartment air-conditioning systems or units to be monitored for maintenance and operating purposes.

5. MANUFACTURED HOMES

Manufactured homes are constructed in factories rather than site built. In 2015, they constituted approximately 6% of all housing units in the United States (EIA 2017). Heating and cooling systems in manufactured homes, as well as other facets of construction such as insulation levels, are regulated in the United States by the Housing and Urban Development (HUD) Manufactured Housing Construction and Safety Standards Act. Each complete home or home section is assembled on a transportation chassis, which is used to transport the home from the factory to the home site and serves as the base of the structure. Manufactured homes vary in size from small, single-floor section units starting at 37 m^2 to large, multiple sections, which when joined together can provide over 280 m^2 and have an appearance similar to site-constructed homes.

Heating systems are factory-installed and are primarily forced-air downflow units feeding main supply ducts built into the subfloor, with floor registers located throughout the home. A small percentage of homes in the far southern and southwestern United States use upflow units feeding overhead ducts in the attic space. Typically, there is no return duct system. Air returns to the air handler from each room through door undercuts, hallways, and a grilled door or louvered panel. The complete heating system is a reduced-clearance type with the air-handling unit installed in a small closet or alcove, usually in a hallway. Sound control measures may be required if large forced-air systems are installed close to sleeping areas. Gas, oil, and electric furnaces or heat pumps may be installed by the home manufacturer to satisfy market requirements.

Gas and oil furnaces are compact direct-vent types approved for installation in a manufactured home. The special venting arrangement used is a vertical through-the-roof concentric pipe-in-pipe system that draws all air for combustion directly from the outdoors and discharges combustion products through a windproof vent terminal. Gas furnaces must be easily convertible from liquefied petroleum gas (LPG) to natural gas and back as required at the final site. In the United States, 54% of manufactured homes use electricity for their heat source, around 22% use natural gas, and 12% use propane (EIA 2017).

Manufactured homes may be cooled with add-on split or single-package air-conditioning systems when supply ducts are adequately sized and rated for that purpose according to HUD requirements. The split-system evaporator coil may be installed in the integral coil cavity provided with the furnace. A high-static-pressure blower is used to overcome resistance through the furnace, evaporator coil, and compact air distribution system. Single-package air conditioners are connected with flexible air ducts to feed existing factory in-floor or overhead ducts. Flexible ducts are installed underneath the mobile home to connect multiple sections; because of their

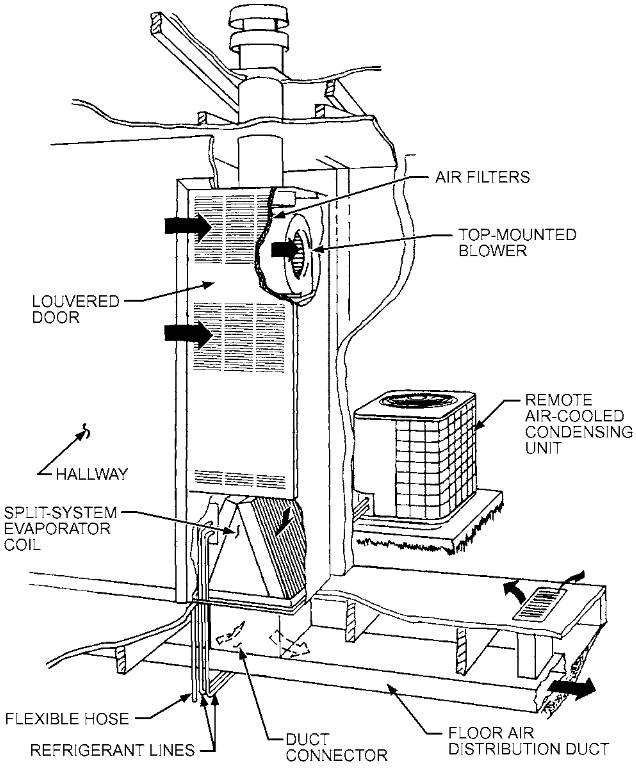

Fig. 5 Typical Installation of Heating and Cooling Equipment for Manufactured Home

location, these ducts may be susceptible to damage by water or animals. Dampers or other means are required to prevent the cooled, conditioned air from backflowing through a furnace cabinet.

A typical installation of a downflow gas or oil furnace with a split-system air conditioner is shown in Figure 5. Air enters the furnace from the hallway, passing through a louvered door on the front of the furnace. The air then passes through air filters and is drawn into the top-mounted blower, which during winter forces air down over the heat exchanger, where it picks up heat. For summer cooling, the blower forces air through the furnace heat exchanger and then through the split-system evaporator coil, which removes heat and moisture from the passing air. During heating and cooling, conditioned air then passes through the floor base via a duct connector before flowing into the floor air distribution duct. The evaporator coil is connected with refrigerant lines to a remote air-cooled condensing unit. The condensate collected at the evaporator is drained by a flexible hose, routed to the exterior through the floor construction, and connected to a suitable drain. Cooling equipment sizing guidelines are provided by the Department of Energy through the ENERGY STAR program for manufactured homes in the continental United States (DOE 2005).

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CHAPTER 2

RETAIL FACILITIES

THIS chapter covers design and application of air-conditioning and heating systems for various retail merchandising facilities. Load calculations, systems, and equipment are covered elsewhere in the Handbook series.

1. GENERAL CRITERIA

To apply equipment properly, the construction of the space to be conditioned, its use and occupancy, the time of day in which greatest occupancy occurs, physical building characteristics, and lighting layout must be known.

The following must also be considered:

- Electric power: size of service
- Heating: availability of steam, hot water, gas, oil, or electricity
- Cooling: availability of chilled water, well water, city water, and water conservation equipment
- Internal heat gains
- Equipment locations
- Structural considerations
- Rigging and delivery of equipment
- Obstructions
- Ventilation: opening through roof or wall for outdoor air duct
- Exposures and number of doors
- Orientation of store
- Code requirements
- Utility rates and regulations
- Building standards

Specific design requirements, such as the increase in outdoor air required to make up for kitchen exhaust, must be considered. Ventilation requirements of ASHRAE *Standard* 62.1 must be followed. Objectionable odors may necessitate special filtering, exhaust, and additional outdoor air intake.

Security requirements must be considered and included in the overall design and application. Minimum considerations require secure equipment rooms, secure air-handling systems, and outdoor air intakes located on the top of facilities. More extensive security measures should be developed based on overall facility design, owner requirements, and local authorities.

Load calculations should be made using the procedures outlined in the *ASHRAE Handbook—Fundamentals*.

Almost all localities have some form of energy code in effect that establishes strict requirements for insulation, equipment efficiencies, system designs, etc., and places strict limits on fenestration and lighting. The requirements of ASHRAE *Standard* 90.1 must be met as a minimum guideline for retail facilities. The *Advanced Energy Design Guide for Small Retail Buildings* (ASHRAE 2006) provides additional energy savings suggestions. In addition, see ASHRAE *Standards* 90.1 and 189.1 for guidance on achieving further energy savings.

Retail facilities often have a high internal sensible heat gain relative to the total heat gain. However, the quantity of outdoor air required by ventilation codes and standards may result in a high latent heat removal demand at the equipment. The high latent heat removal requirement may also occur at outdoor dry-bulb temperatures below design. Unitary HVAC equipment and HVAC systems should be designed and selected to provide the necessary sensible and latent heat removal. The equipment, systems, and controls should be designed to provide the necessary temperature, ventilation, filtration, and humidity conditions.

HVAC system selection and design for retail facilities are normally determined by economics. First cost is usually the determining factor for small stores. For large retail facilities, owning, operating, and maintenance costs are also considered. Decisions about mechanical systems for retail facilities are typically based on a cash flow analysis rather than on a full life-cycle analysis.

HVAC system provisions are provided initially in most retail facilities, including strip centers, malls, and retail centers in high-rise buildings. Provisions may include condenser water pipes or stub out for fresh air intake in multiple points to satisfy a 93 m^2 module. In strip centers, roof top unit provisions should be provided.

2. SMALL STORES

Small stores are typically located in convenience centers and may have at least the store front exposed to outdoor weather, although some are free standing. Large glass areas found at the front of many small stores may cause high peak solar heat gain unless they have northern exposures or large overhanging canopies. High heat loss may be experienced on cold, cloudy days in the front of these stores. The HVAC system for this portion of the small store should be designed to offset the greater cooling and heating requirements. Entrance vestibules, entry heaters, and/or air curtains may be needed in some climates.

Design Considerations

System Design. Single-zone unitary rooftop equipment is common in store air conditioning. Using multiple units to condition the store involves less ductwork and can maintain comfort in the event of partial equipment failure. Prefabricated and matching curbs simplify installation and ensure compatibility with roof materials.

Air to air heat pumps, offered as packaged equipment, are readily adaptable to small-store applications. Ground-source and other closed-loop heat pump systems have been provided for small stores where the requirements of several users may be combined. Winter design conditions, utility rates, maintenance costs, and operating costs should be compared to those of conventional heating HVAC systems before this type of system is chosen. Consider providing a defrost cycle: in cold climates, snow cover may not allow fresh air into the building.

Water-cooled unitary equipment is available for small-store air conditioning. However, many communities restrict the use of city water and groundwater for condensing purposes and may require

The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

installation of a cooling tower. Water-cooled equipment generally operates efficiently and economically.

Air Distribution. External static pressures available in small-store air-conditioning units are limited, and air distribution should be designed to keep duct resistances low. Duct velocities should not exceed 6 m/s, and pressure drop should not exceed 0.8 Pa/m. Average air quantities, typically range from 47 to 60 L/s per kilowatt of cooling in accordance with the calculated internal sensible heat load.

Pay attention to suspended obstacles (e.g., lights, soffits, ceiling recesses, and displays) that interfere with proper air distribution.

The duct system should contain enough dampers for air balancing. Volume dampers should be installed in takeoffs from the main supply duct to balance air to the branch ducts. Dampers should be installed in the return and outdoor air ducts for proper outdoor air/return air balance and for economizer operation.

Control. Controls for small stores should be kept as simple as possible while still providing the required functions. Unitary equipment is typically available with manufacturer-supplied controls for easy installation and operation.

Automatic dampers should be placed in outdoor air inlets and in exhausts to prevent air entering when the fan is turned off.

Heating controls vary with the nature of the heating medium. Duct heaters are generally furnished with manufacturer-installed safety controls. Steam or hot-water heating coils require a motorized valve for heating control. Take care in preventing coil freezing.

Open platform units for any direct digital control (DDC) should provide the necessary options for remote control. Time clock control can limit unnecessary HVAC operation. Unoccupied reset controls should be provided in conjunction with timed control.

Maintenance. To protect the initial investment and ensure maximum efficiency, maintenance of air-conditioning units in small stores should be provided by a reliable service company on a yearly basis. The maintenance agreement should clearly specify responsibility for filter replacements, lubrication, belts, coil cleaning, adjustment of controls, refrigeration cycle maintenance, replacement of refrigerant, pump repairs, electrical maintenance, winterizing, system start-up, and extra labor required for repairs.

Improving Operating Cost. Outdoor air economizers can reduce the operating cost of cooling in most climates. They are generally available as factory options or accessories with roof-mounted units. Increased exterior insulation generally reduces operating energy requirements and may in some cases allow the size of installed equipment to be reduced. Most codes now include minimum requirements for insulation and fenestration materials. The *Advanced Energy Design Guide for Small Retail Buildings* (ASHRAE 2006) provides additional energy savings suggestions.

3. DISCOUNT, BIG-BOX, AND SUPERCENTER STORES

Large discount, big-box, and supercenter stores attract customers with discount prices. These stores typically have high-bay fixture displays and usually store merchandise in the sales area. They feature a wide range of merchandise and may include such diverse areas as a food service area, auto service area, supermarket, pharmacy, bank, and garden shop. Some stores sell pets, including fish and birds. This variety of activity must be considered in designing the HVAC systems. The design and application suggestions for small stores also apply to discount stores.

Each specific area is typically treated as a traditional stand-alone facility would be. Conditioning outdoor air for all areas must be considered to limit the introduction of excess moisture that will migrate to the freezer aisles of a grocery area.

Hardware, lumber, furniture, etc., is also sold in big-box facilities. A particular concern in this type of facility is ventilation for merchandise and material-handling equipment, such as forklift trucks.

In addition, areas such as stockrooms, rest rooms, break rooms, offices, and special storage rooms for perishable merchandise may require separate HVAC systems or refrigeration.

Load Determination

Operating economics and the spaces served often dictate indoor design conditions. Some stores may base summer load calculations on a higher indoor temperature (e.g., 27°C db) but then set the thermostats to control at 22 to 24°C db. This reduces the installed equipment size while providing the desired indoor temperature most of the time.

Heat gain from lighting is not uniform throughout the entire area. For example, jewelry and other specialty displays typically have lighting heat gains of 65 to 85 W/m^2 of floor area, whereas the typical sales area has an average value of 20 to 40 W/m^2. For stockrooms and receiving, marking, toilet, and rest room areas, a value of 20 W/m^2 may be used. When available, actual lighting layouts rather than average values should be used for load computation. With LED lighting, these watt gains should be reduced substantially. See ASHRAE *Standard* 189.1 for further ideas for reduction.

ASHRAE *Standards* 62.1 and 90.1 provide data and population density information to be used for load determination. Chapter 34 of this volume has specific information on ventilation systems for kitchens and food service areas. Ventilation and outdoor air must be provided as required in ASHRAE *Standard* 62.1 and local codes.

Data on the heat released by special merchandising equipment, such as amusement rides for children or equipment used for preparing specialty food items (e.g., popcorn, pizza, frankfurters, hamburgers, doughnuts, roasted chickens, cooked nuts, etc.), should be obtained from the equipment manufacturers.

Design Considerations

Heat released by installed lighting is often sufficient to offset the design roof heat loss. Therefore, interior areas of these stores need cooling during business hours throughout the year. Perimeter areas, especially the storefront and entrance areas, may have highly variable heating and cooling requirements. Proper zone control and HVAC design are essential. Location of checkout lanes in the storefront or entrance areas makes proper environmental zone control even more important.

System Design. The important factors in selecting discount, big-box, and supercenter store air-conditioning systems are (1) installation costs, (2) floor space required for equipment, (3) maintenance requirements, (4) equipment reliability, and (5) simplicity of control. Roof-mounted units are most commonly used.

Air Distribution. The air supply for large interior sales areas should generally be designed to satisfy the primary cooling requirement. For perimeter areas, the variable heating and cooling requirements must be considered.

Because these stores require high, clear areas for display and restocking, air is generally distributed from heights of 4.3 m and greater. Air distribution at these heights requires high discharge velocities in the heating season to overcome the buoyancy of hot air. This discharge air velocity creates turbulence in the space and induces airflow from the ceiling area to promote complete mixing. Space-mounted fans, and radiant heating at the perimeter, entrance heaters, and air curtains may be required.

Control. Because the controls are usually operated by personnel who have little knowledge of air conditioning, systems should be kept as simple as possible while still providing the required functions. Unitary equipment is typically available with manufacturer-supplied controls for easy installation and operation.

Automatic dampers should be placed in outdoor air inlets and in exhausts to prevent air entering when the fan is turned off.

Heating controls vary with the nature of the heating medium. Duct heaters are generally furnished with manufacturer-installed safety controls. Steam or hot-water heating coils require a motorized valve for heating control.

Open-platform DDC control should provide the necessary options for remote control.

Maintenance. Most stores do not employ trained HVAC maintenance personnel; they rely instead on service contracts with either the installer or a local service company. (See the section on Small Stores).

Improving Operating Cost. See the section on Small Stores.

4. SUPERMARKETS

Load Determination

Heating and cooling loads should be calculated using the methods outlined in Chapter 18 of the 2017 *ASHRAE Handbook—Fundamentals*. In supermarkets, space conditioning is required both for human comfort and for proper operation of refrigerated display cases. The air-conditioning unit should introduce a minimum quantity of outdoor air, either the volume required for ventilation based on ASHRAE *Standard* 62.1 or the volume required to maintain slightly positive pressure in the space, whichever is larger.

Many supermarkets are units of a large chain owned or operated by a single company. The standardized construction, layout, and equipment used in designing many similar stores simplify load calculations.

It is important that the final air-conditioning load be correctly determined. Refer to manufacturers' data for information on total heat extraction, sensible heat, latent heat, and percentage of latent to total load for display cases. Engineers report considerable fixture heat removal (case load) variation as the relative humidity and temperature vary in comparatively small increments. Relative humidity above 55% substantially increases the load; reduced absolute humidity substantially decreases the load, as shown in Figure 1. Trends in store design, which include more food refrigeration and more efficient lighting, reduce the sensible component of the load even further.

To calculate the total load and percentage of latent and sensible heat that the air conditioning must handle, the refrigerating effect imposed by the display fixtures must be subtracted from the building's gross air-conditioning requirements (Table 1).

Modern supermarket designs have a high percentage of closed refrigerated display fixtures. These vertical cases have large glass display doors and greatly reduce the problem of latent and sensible heat removal from the occupied space. The doors do, however, require heaters to minimize condensation and fogging. These heaters should cycle by automatic control.

For more information on supermarkets, see Chapter 15 in the 2018 *ASHRAE Handbook—Refrigeration*.

Design Considerations

Store owners and operators frequently complain about cold aisles, heaters that operate even when the outdoor temperature is above 21°C, and air conditioners that operate infrequently. These problems are usually attributed to spillover of cold air from open refrigerated display equipment.

Although refrigerated display equipment may cause cold stores, the problem is not excessive spillover or improperly operating equipment. Heating and air-conditioning systems must compensate for the effects of open refrigerated display equipment. Design considerations include the following:

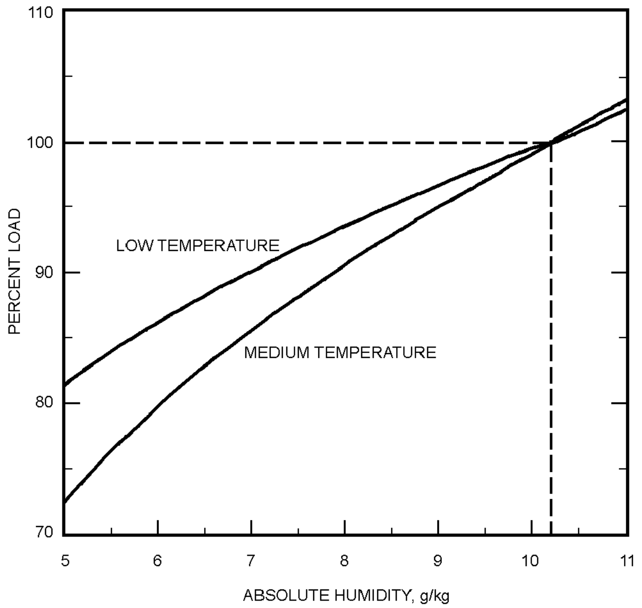

Fig. 1 Refrigerated Case Load Variation with Store Air Humidity

Table 1 Refrigerating Effect (RE) Produced by Open Refrigerated Display Fixtures

	RE on Building Per Unit Length of Fixture*			
Display Fixture Types	**Latent Heat, W/m**	**% Latent to Total RE**	**Sensible Heat, W/m**	**Total RE, W/m**
Low-temperature (frozen food)				
Single-deck	36	15	199	235
Single-deck/double-island	67	15	384	451
2-deck	138	20	554	692
3-deck	310	20	1238	1548
4- or 5-deck	384	20	1538	1922
Ice cream				
Single-deck	62	15	352	414
Single-deck/double-island	67	15	384	451
Standard-temperature				
Meats				
Single-deck	50	15	286	336
Multideck	211	20	842	1053
Dairy, multideck	188	20	754	942
Produce				
Single-deck	35	15	196	231
Multideck	184	20	738	922

*These figures are general magnitudes for fixtures adjusted for average desired product temperatures and apply to store ambients in front of display cases of 22.2 to 23.3°C with 50 to 55% rh. Raising the dry bulb only 2 to 3 K and the humidity to 5 to 10% can increase loads (heat removal) 25% or more. Lower temperatures and humidities, as in winter, have an equally marked effect on lowering loads and heat removal from the space. Consult display case manufacturer's data for the particular equipment to be used.

- Increased heating requirement because of removal of large quantities of heat, even in summer.
- Net air-conditioning load after deducting the latent and sensible refrigeration effect. The load reduction and change in sensible-latent load ratio have a major effect on equipment selection.
- Need for special air circulation and distribution to offset the heat removed by open refrigerating equipment.
- Need for independent temperature and humidity control.

Each of these problems is present to some degree in every supermarket, although situations vary with climate and store layout. Methods of overcoming these problems are discussed in the following sections. Energy costs may be extremely high if the year-round air-conditioning system has not been designed to compensate for the effects of refrigerated display equipment.

Heat Removed by Refrigerated Displays. The display refrigerator not only cools a displayed product but also envelops it in a blanket of cold air that absorbs heat from the room air in contact with it. Approximately 80 to 90% of the heat removed from the room by vertical refrigerators is absorbed through the display opening. Thus, the open refrigerator acts as a large air cooler, absorbing heat from the room and rejecting it via the condensers outside the building. Occasionally, this conditioning effect can be greater than the design air-conditioning capacity of the store. The heat removed by the refrigeration equipment *must* be considered in the design of the air-conditioning and heating systems because this heat is being removed constantly, day and night, summer and winter, regardless of the store temperature. Display cases should be provided with sliding doors to minimize heat loss (see ASHRAE *Standard* 189.1).

Display cases increase the building heating requirement such that heat is often required at unexpected times. The following example shows the extent of this cooling effect. The desired store temperature is 24°C. Store heat loss or gain is assumed to be 8 kW/K of temperature difference between outdoor and store temperature. (This value varies with store size, location, and exposure.) The heat removed by refrigeration equipment is 56 kW. (This value varies with the number of refrigerators.) The latent heat removed is assumed to be 19% of the total, leaving 81% or 45.4 kW sensible heat removed, which cools the store 45.4/8 = 5.7 K. By constantly removing sensible heat from its environment, the refrigeration equipment in this store will cool the store 5.7 K below outdoor temperature in winter and in summer. Thus, in mild climates, heat must be added to the store to maintain comfort conditions.

The designer can either discard or reclaim the heat removed by refrigeration. If economics and store heat data indicate that the heat should be discarded, heat extraction from the space must be included in the heating load calculation. If this internal heat loss is not included, the heating system may not have sufficient capacity to maintain design temperature under peak conditions.

The additional sensible heat removed by the cases may change the air-conditioning latent load ratio from 32% to as much as 50% of the net heat load. Removing a 50% latent load by refrigeration alone is very difficult. Normally, it requires specially designed equipment with reheat or chemical adsorption.

Multishelf refrigerated display equipment requires 55% rh or less. In the dry-bulb temperature ranges of average stores, humidity in excess of 55% can cause heavy coil frosting, product zone frosting in low-temperature cases, fixture sweating, and substantially increased refrigeration power consumption.

A humidistat can be used during summer cooling to control humidity by transferring heat from the condenser to a heating coil in the airstream. The store thermostat maintains proper summer temperature conditions. Override controls prevent conflict between the humidistat and the thermostat.

The equivalent result can be accomplished with a conventional air-conditioning system by using three- or four-way valves and reheat condensers in the ducts. This system borrows heat from the standard condenser and is controlled by a humidistat. For higher energy efficiency, specially designed equipment should be considered. Desiccant dehumidifiers and heat pipes have also been used.

Humidity. Cooling from refrigeration equipment does not preclude the need for air conditioning. On the contrary, it increases the need for humidity control.

With increases in store humidity, heavier loads are imposed on the refrigeration equipment, operating costs rise, more defrost periods are required, and the display life of products is shortened. The dew point rises with relative humidity, and sweating can become so profuse that even nonrefrigerated items such as shelving superstructures, canned products, mirrors, and walls may sweat.

Lower humidity results in lower operating costs for refrigerated cases. There are three methods to reduce the humidity level: (1) standard air conditioning, which may overcool the space when the latent load is high and sensible load is low; (2) mechanical dehumidification, which removes moisture by lowering the air temperature to its dew point, and uses hot-gas reheat when needed to discharge at any desired temperature; and (3) desiccant dehumidification, which removes moisture independent of temperature, supplying warm air to the space unless postcooling is provided to discharge at any desired temperature.

Each method provides different dew-point temperatures at different energy consumption and capital expenditures. The designer should evaluate and consider all consequential trade-offs. Standard air conditioning requires no additional investment but reduces the space dew-point temperature only to 16 to 18°C. At 24°C space temperature this results in 60 to 70% rh at best. Mechanical dehumidifiers can provide humidity levels of 40 to 50% at 24°C. Supply air temperature can be controlled with hot-gas reheat between 10 and 32°C. Desiccant dehumidification can provide levels of 35 to 40% rh at 24°C. Postcooling supply air may be required, depending on internal sensible loads. A desiccant is reactivated by passing hot air at 80 to 121°C through the desiccant base. Consider adding a heat recovery system to maintain low humidity and using the recovered heat for reheat.

System Design. The same air-handling equipment and distribution system are generally used for both cooling and heating. The entrance area is the most difficult section to heat. Many supermarkets in the northern United States are built with vestibules provided with separate heating equipment to temper the cold air entering from the outdoors. Auxiliary heat may also be provided at the checkout area, which is usually close to the front entrance. Methods of heating entrance areas include the use of (1) air curtains, (2) gas-fired or electric infrared radiant heaters, and (3) waste heat from the refrigeration condensers.

Air-cooled condensing units are the most commonly used in supermarkets. Typically, a central air handler conditions the entire sales area. Specialty areas like bakeries, computer rooms, or warehouses are better served with a separate air handler because the loads in these areas vary and require different control than the sales area.

Most installations are made on the roof of the supermarket. If air-cooled condensers are located on the ground outside the store, they must be protected against vandalism as well as truck and customer traffic. If water-cooled condensers are used on the air-conditioning equipment and a cooling tower is required, provisions should be made to prevent freezing during winter operation.

Air Distribution. Designers overcome the concentrated load at the front of a supermarket by discharging a large portion of the total air supply into the front third of the sales area.

The air supply to the space with a standard air-conditioning system is typically 5 L/s per square metre of sales area. This value should be calculated based on the sensible and latent internal loads. The desiccant system typically requires less air supply because of its high moisture removal rate, typically 2.5 L/s per square metre. Mechanical dehumidification can fall within these parameters, depending on required dew point and suction pressure limitations.

Being denser, air cooled by the refrigerators settles to the floor and becomes increasingly colder, especially in the first 900 mm above the floor. If this cold air remains still, it causes discomfort and does not help to cool other areas of the store that need more cooling. Cold floors or areas in the store cannot be eliminated by

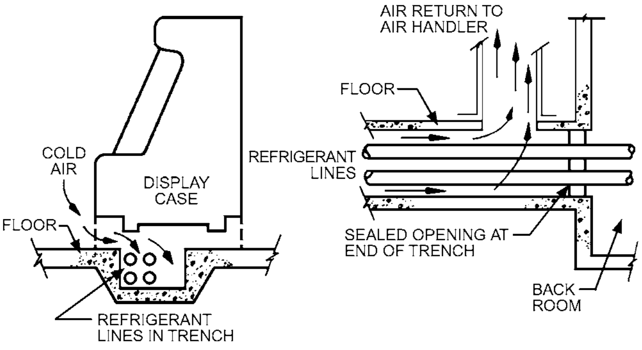

Fig. 2 Floor Return Ducts

the simple addition of heat. Reduction of air-conditioning capacity without circulation of localized cold air is analogous to installing an air conditioner without a fan. To take advantage of the cooling effect of the refrigerators and provide an even temperature in the store, the cold air must be mixed with the general store air.

To accomplish the necessary mixing, air returns should be located at floor level; they should also be strategically placed to remove the cold air near concentrations of refrigerated fixtures. Returns should be designed and located to avoid creating drafts. There are two general solutions to this problem:

- **Return Ducts in Floor.** This is the preferred method and can be accomplished in two ways. The floor area in front of the refrigerated display cases is the coolest area. Refrigerant lines are run to all of these cases, usually in tubes or trenches. If the trenches or tubes are enlarged and made to open under the cases for air return, air can be drawn in from the cold area (Figure 2). The air is returned to the air-handling unit through a tee connection to the trench before it enters the back room area. The opening through which the refrigerant lines enter the back room should be sealed.

  If refrigerant line conduits are not used, air can be returned through inexpensive underfloor ducts. If refrigerators have insufficient undercase air passage, consult the manufacturer. Often they can be raised off the floor approximately 40 mm. Floor trenches can also be used as ducts for tubing, electrical supply, and so forth.

  Floor-level return relieves the problem of localized cold areas and cold aisles and uses the cooling effect for store cooling, or increases the heating efficiency by distributing the air to areas that need it most.
- **Fans Behind Cases.** If ducts cannot be placed in the floor, circulating fans can draw air from the floor and discharge it above the cases (Figure 3). Although this approach prevents objectionable cold aisles in front of the refrigerated display cases, it does not prevent an area with a concentration of refrigerated fixtures from remaining colder than the rest of the store.

Control. Store personnel should only be required to change the position of a selector switch to start or stop the system or to change from heating to cooling or from cooling to heating. Control systems for heat recovery applications are more complex and should be coordinated with the equipment manufacturer.

Maintenance and Heat Reclamation. Most supermarkets, except large chains, do not employ trained maintenance personnel, but rather rely on service contracts with either the installer or a local service company. This relieves store management of the responsibility of keeping the air conditioning operating properly.

Heat extracted from the store and heat of compression may be reclaimed for heating cost saving. One method of reclaiming rejected heat is to use a separate condenser coil located in the air conditioner's air handler, either alternately or in conjunction with the

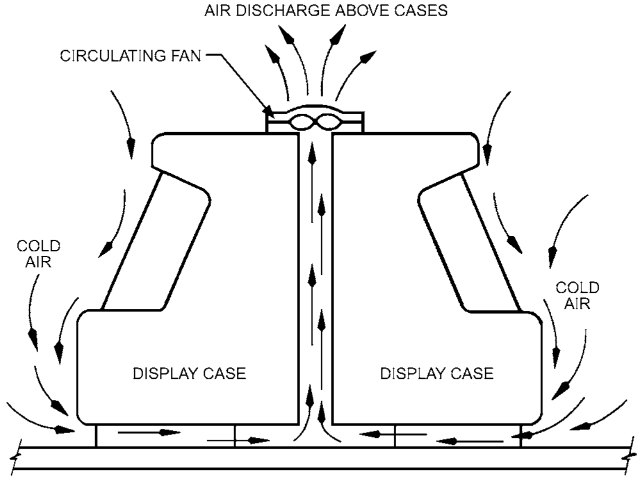

Fig. 3 Air Mixing Using Fans Behind Cases

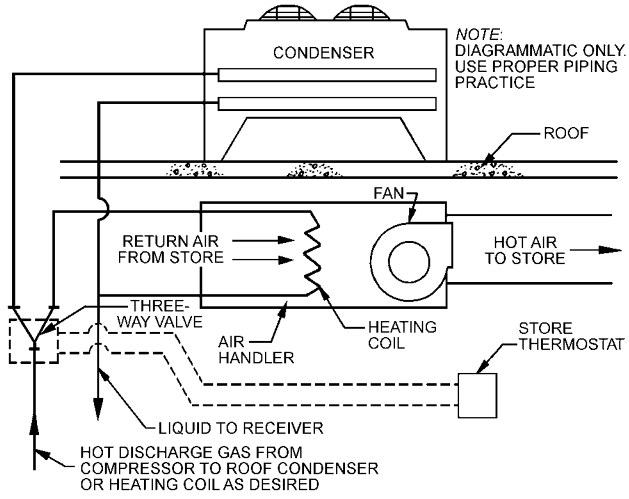

Fig. 4 Heat Reclaiming Systems

main refrigeration condensers, to provide heat as required (Figure 4). Another system uses water-cooled condensers and delivers its rejected heat to a water coil in the air handler.

The heat rejected by conventional machines using air-cooled condensers may be reclaimed by proper duct and damper design (Figure 5). Automatic controls can either reject this heat to the outdoors or recirculate it through the store. Consider using warm liquid defrost for evaporator coils on refrigerated cases, coolers, and freezers (Mei et al. 2002).

5. DEPARTMENT STORES

Department stores vary in size, type, and location, so air-conditioning design should be specific to each store. Essential features of a quality system include (1) an automatic control system properly designed to compensate for load fluctuations, (2) zoned air distribution to maintain uniform conditions under shifting loads, and (3) use of outdoor air for cooling during favorable conditions. It is also desirable to adjust indoor temperature for variations in outdoor temperature. Although close control of humidity is not necessary, a properly designed system should operate to maintain relative humidity at 50% or below. This humidity limit eliminates musty odors and retards perspiration, particularly in fitting rooms.

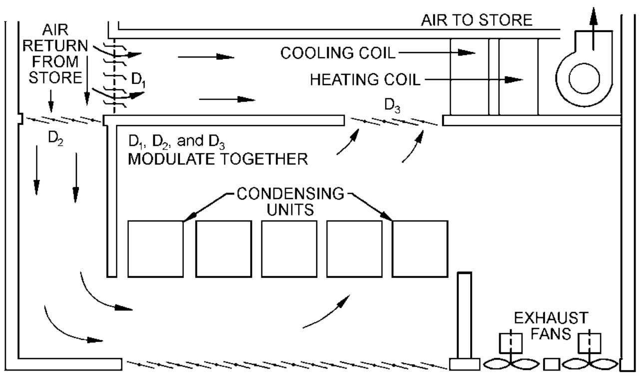

Fig. 5 Machine Room with Automatic Temperature Control Interlocked with Store Temperature Control

Table 2 Approximate Lighting Load for Older Department Stores

Area	W/m²
Basement	30 to 50
First floor	40 to 70
Upper floors, women's wear	30 to 50
Upper floors, house furnishings	20 to 30

Load Determination

Because the occupancy (except store personnel) is transient, indoor conditions are commonly set not to exceed 26°C db and 50% rh at outdoor summer design conditions, and 21°C db at outdoor winter design conditions. Winter humidification is seldom used in store air conditioning.

ASHRAE *Standard* 62.1 provides population density information for load determination purposes. Energy codes and standards restrict installed lighting watt density for newly constructed facilities. However, older facilities may have increased lighting watt densities. Values in Table 2 are approximations for older facilities.

Other loads, such as those from motors, beauty parlors, restaurant equipment, and any special display or merchandising equipment, should be determined.

Minimum outdoor air requirements should be as defined in ASHRAE *Standard* 62.1 or local codes.

Paint shops, alteration rooms, rest rooms, eating places, and locker rooms should be provided with positive exhaust ventilation, and their requirements must be checked against local codes.

Design Considerations

Before performing load calculations, the designer should examine the store arrangement to determine what will affect the load and the system design. For existing buildings, actual construction, floor arrangement, and load sources can be surveyed. For new buildings, examination of the drawings and discussion with the architect or owner is required.

Larger stores may contain beauty parlors, food service areas, extensive office areas, auditoriums, warehouse space, etc. Some of these special areas may operate during hours in addition to the normal store-open hours. If present or future operation could be compromised by such a strategy, these spaces should be served by separate HVAC systems. Because of the concentrated load and exhaust requirements, beauty parlors and food service areas should be provided with separate ventilation and air distribution.

Future plans for the store must be ascertained because they can have a great effect on the type of air conditioning and refrigeration to be used.

System Design. Air conditioning systems for department stores may use unitary or central station equipment. Selection should be based on owning and operating costs as well as special considerations for the particular store, such as store hours, load variations, and size of load.

Large department stores have often used central-station systems consisting of air-handling units having chilled-water cooling coils, hot-water heating coils, fans, and filters. Some department stores now use large unitary units. Air systems must have adequate zoning for varying loads, occupancy, and usage. Wide variations in people loads may justify considering variable-volume air distribution systems. Water chilling and heating plants distribute water to the various air handlers and zones and may take advantage of some load diversity throughout the building.

Air-conditioning equipment should not be placed in the sales area; instead, it should be located in mechanical equipment room areas or on the roof whenever practicable. Ease of maintenance and operation must be considered in the design of equipment rooms and locations.

Many locations require provisions for smoke removal. This is normally accommodated through the roof and may be integrated with the HVAC system.

Air Distribution. All buildings must be studied for orientation, wind exposure, construction, and floor arrangement. These factors affect not only load calculations, but also zone arrangements and duct locations. In addition to entrances, wall areas with significant glass, roof areas, and population densities, the expected locations of various departments should be considered. Flexibility must be left in the duct design to allow for future movement of departments. It may be necessary to design separate air systems for entrances, particularly in northern areas. This is also true for storage areas where cooling is not contemplated.

Air curtains may be installed at entrance doorways to limit infiltration of unconditioned air, at the same time providing greater ease of entry.

Control. Space temperature controls are usually operated by personnel who have little knowledge of air conditioning. Therefore, exposed sensors and controls should be kept as simple as possible while still providing the required functions.

Control must be such that correctly conditioned air is delivered to each zone. Outdoor air intake should be automatically controlled to operate at minimum cost while providing required airflow. Partial or full automatic control should be provided for cooling to compensate for load fluctuations. Completely automatic refrigeration plants should be considered.

Heating controls vary with the nature of the heating medium. Duct heaters are generally furnished with manufacturer-installed safety controls. Steam or hot-water heating coils require a motorized valve for heating control.

Time clock control can limit unnecessary HVAC operation. Unoccupied reset controls should be provided in conjunction with timed control.

Automatic dampers should be placed in outdoor air inlets and in exhausts to prevent air entering when the fan is turned off.

Maintenance. Most department stores employ personnel for routine housekeeping, operation, and minor maintenance, but rely on service and preventive maintenance contracts for refrigeration cycles, chemical treatment, central plant systems, and repairs.

Improving Operating Cost. An outdoor air economizer can reduce the operating cost of cooling in most climates. These are generally available as factory options or accessories with the air-handling units or control systems. Heat recovery and desiccant dehumidification should also be analyzed.

6. CONVENIENCE CENTERS

Many small stores, discount stores, supermarkets, drugstores, theaters, and even department stores are located in convenience centers. The space for an individual store is usually leased. Arrangements for installing air conditioning in leased space vary. Typically, the developer builds a shell structure and provides the tenant with an allowance for usual heating and cooling and other minimum interior finish work. The tenant must then install an HVAC system. In another arrangement, developers install HVAC units in the small stores with the shell construction, often before the space is leased or the occupancy is known. Larger stores typically provide their own HVAC design and installation.

Design Considerations

The developer or owner may establish standards for typical heating and cooling that may or may not be sufficient for the tenant's specific requirements. The tenant may therefore have to install systems of different sizes and types than originally allowed for by the developer. The tenant must ascertain that power and other services will be available for the total intended requirements.

The use of party walls in convenience centers tends to reduce heating and cooling loads. However, the effect an unoccupied adjacent space has on the partition load must be considered.

7. REGIONAL SHOPPING CENTERS

Regional shopping centers generally incorporate an enclosed, heated and air-conditioned mall. These centers are normally owned by a developer, who may be an independent party, a financial institution, or one of the major tenants in the center.

Some regional shopping centers are designed with an open pedestrian mall between rows of stores. This open-air concept results in tenant spaces similar to those in a convenience center. Storefronts and other perimeters of the tenant spaces are exposed to exterior weather conditions.

Major department stores in shopping centers are typically considered separate buildings, although they are attached to the mall. The space for individual small stores is usually leased. Arrangements for installing air conditioning in the individually leased spaces vary, but are similar to those for small stores in convenience centers.

Table 3 presents typical data that can be used as check figures and field estimates. However, this table should not be used for final determination of load, because the values are only averages.

Design Considerations

The owner or developer provides the HVAC system for an enclosed mall. The regional shopping center may use a central plant or unitary equipment. The owner generally requires that the individual tenant stores connect to a central plant and includes charges for heating and cooling services. Where unitary systems are used, the owner generally requires that the individual tenant install a unitary system of similar design. Because of different functions and load profiles, systems should be designed to recover heat transfer from one area and transfer to the other to save annual energy consumption.

The owner may establish standards for typical heating and cooling systems that may or may not be sufficient for the tenant's specific requirements. Therefore, the tenant may have to install systems of different sizes than originally allowed for by the developer.

Leasing arrangements may include provisions that have a detrimental effect on conservation (such as allowing excessive lighting and outdoor air or deleting requirements for economizer systems). The designer of HVAC for tenants in a shopping center must be well aware of the lease requirements and work closely with leasing agents to guide these systems toward better energy efficiency.

Many regional shopping centers contain specialty food court areas that require special considerations for odor control, outdoor air requirements, kitchen exhaust, heat removal, and refrigeration equipment.

System Design. Regional shopping centers vary widely in physical arrangement and architectural design. Single-level and smaller centers usually use unitary systems for mall and tenant air conditioning; multilevel and larger centers usually use a central system. The owner sets the design of the mall and generally requires that similar systems be installed for tenant stores.

A typical central system may distribute chilled air to individual tenant stores and to the mall air-conditioning system and use variable-volume control and electric heating at the local use point. Some plants distribute both hot and chilled water. Some all-air systems also distribute heated air. Central plant systems typically provide improved efficiency and better overall economics of operation. Central systems may also provide the basic components required for smoke removal.

Air Distribution. Air distribution in individual stores should be designed for the particular space occupancy. Some tenant stores maintain a negative pressure relative to the public mall for odor control.

The total facility HVAC system should maintain a slight positive pressure relative to atmospheric pressure and a neutral pressure relative between most of the individual tenant stores. Exterior entrances should have vestibules.

Smoke management is required by many building codes, so air distribution should be designed to easily accommodate smoke control requirements.

Maintenance. Methods for ensuring the operation and maintenance of HVAC systems in regional shopping centers are similar to those used in department stores. Individual tenant stores may have to provide their own maintenance.

Improving Operating Cost. Methods for lowering operating costs in shopping centers are similar to those used in department stores. Some shopping centers have successfully used cooling tower heat exchanger economizers.

Central plant systems for regional shopping centers typically have lower operating costs than unitary systems. However, the initial cost of the central plant system is typically higher.

Table 3 Typical Installed Cooling Capacity and Lighting Levels: Midwestern United States

Type of Space	Area per Unit of Installed Cooling, m^2/kW	Installed Cooling per Unit of Area, W/m^2	Lighting Density of Area, W/m^2	Annual Lighting Energy Use,[a] kWh/m^2
Dry retail[b]	9.69	104.1	43.1	174.4
Restaurant	3.59	277.6	21.5	87.2
Fast food				
Food court tenant area	4.23	236.6	32.3	131.3
Food court seating area	3.88	258.7	32.3	131.3
Mall common area	7.61	135.6	32.3	131.3[c]
Total	6.97	142.0	38.8	157.2

Source: Based on 2001 Data—Midwestern United States.
[a]Hours of operating lighting assumes 12 h/day and 6.5 days/week.
[b]Jewelry, high-end lingerie, and some other occupancy lighting levels are typically 65 to 85 120 W/m^2 and can range to 120 W/m^2. Cooling requirements for these spaces are higher.
[c]62.4 kWh/m^2 for centers that shut off lighting during daylight, assuming 6 h/day and 6.2 days/week.

8. MULTIPLE-USE COMPLEXES

Multiple-use complexes are being developed in many metropolitan areas. These complexes generally combine retail facilities with other facilities such as offices, hotels, residences, or other commercial space into a single site. This consolidation of facilities into a single site or structure provides benefits such as improved land use; structural savings; more efficient parking; utility savings; and opportunities for more efficient electrical, fire protection, and mechanical systems.

Load Determination

The various occupancies may have peak HVAC demands that occur at different times of the day or year. Therefore, the HVAC loads of these occupancies should be determined independently. Where a combined central plant is considered, a block load should also be determined.

Design Considerations

Retail facilities are generally located on the lower levels of multiple-use complexes, and other commercial facilities are on upper levels. Generally, the perimeter loads of the retail portion differ from those of the other commercial spaces. Greater lighting and population densities also make HVAC demands for the retail space different from those for the other commercial space.

The differences in HVAC characteristics for various occupancies within a multiple-use complex indicate that separate air handling and distribution should be used for the separate spaces. However, combining the heating and cooling requirements of various facilities into a central plant can achieve a substantial saving. A combined central heating and cooling plant for a multiple-use complex also provides good opportunities for heat recovery, thermal storage, and other similar functions that may not be economical in a single-use facility.

Many multiple-use complexes have atriums. The stack effect created by atriums requires special design considerations for tenants and space on the main floor. Areas near entrances require special measures to prevent drafts and accommodate extra heating requirements.

System Design. Individual air-handling and distribution systems should be designed for the various occupancies. The central heating and cooling plant may be sized for the block load requirements, which may be less than the sum of each occupancy's demand.

Control. Multiple-use complexes typically require centralized control. It may be dictated by requirements for fire and smoke control, security, remote monitoring, billing for central facilities use, maintenance control, building operations control, and energy management.

9. SUSTAINABILITY AND ENERGY EFFICIENCY

Many large retail chains have made significant advances in implementing sustainability programs. Many retailers have added leaders who focus on energy efficiency and sustainability to their executive leadership teams, and some even establish and report sustainability goals (Jamieson et al. 2013). ASHRAE *Standard* 90.1 and appropriate design guides and tools should be used to achieve energy efficiency and sustainable design in a retail facility.

A dedicated integrated design group is helpful in developing and implementing energy efficient design strategies. The design team should be open to new and innovative energy-efficient designs that may include geothermal heating and cooling, high-performance lighting, heat recovery systems, high-efficiency HVAC, and renewable energy systems (Duarte 2013; Genest and Charneux 2005).

Design engineers should take advantage of ASHRAE's *Advanced Energy Design Guides* (www.ashrae.org/technical-resources/aedgs) to reduce energy-related expenses and to achieve retailer's corporate sustainability targets. While incorporating energy efficiency measures, HVAC design engineers should consider items such as heating and cooling loads, ventilation, energy management systems, variable-speed fan controls, variable-speed pumps, variable-frequency drives, and energy recovery systems; it is most important, however, to understand the needs of the facility. When energy-efficient measures are properly implemented, they can lead to achieving a retailer's corporate sustainable mission, higher employee morale, and reduced energy costs. Integrated design process (IDP), described in Chapter 60, should be used. IDP promotes collaboration between a retailer's sustainability goals and actual energy-saving strategies. In IDP, all stakeholders work together on a common goal, "result[ing] in a coordinated, constructible, and cost-effective design" (ASHRAE 2011).

Important elements of IDP are

- Project kickoff
- Programming and project design
- Schematic design
- Design development
- Construction documents
- Bid phase
- Construction administration
- Commissioning
- Operations and maintenance
- Continuous improvement
- Controlling costs

Building energy modeling and energy benchmarking tools should be used to estimate energy consumptions, building behavior, evaluation of energy use, and tracking. Chapter 19 of the 2017 *ASHRAE Handbook—Fundamentals* provides more information on energy modeling methodologies. Commonly used benchmarking tools include U.S. EPA ENERGY STAR Portfolio Manager (portfoliomanager.energystar.gov) and Lawrence Berkeley National Laboratory's (LBNL) Standard Energy Efficiency Data Platform™ (www.energy.gov/eere/buildings/standard-energy-efficiency-data-platform). To achieve sustainability and energy efficiency in a retail facility, combined heat and power (CHP) and renewable energy technologies such as solar thermal, solar photovoltaic, wind, and biomass can be considered in conjunction with energy-efficient measures.

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CHAPTER 3

COMMERCIAL AND PUBLIC BUILDINGS

THIS chapter contains technical, environmental, and design considerations to assist the design engineer in the proper application of HVAC systems and equipment for commercial and public buildings.

1. OFFICE BUILDINGS

General Design Considerations

Despite cyclical market fluctuations, office buildings are considered the most complex and competitive segments of real estate development. Survey data of 824 000 office buildings (EIA 2003) demonstrate the distribution of the U.S. office buildings by the numbers and the area, as shown in Table 1.

According to Gause (1998), an office building can be divided into the following categories:

Class. The most basic feature, class represents the building's quality by taking into account variables such as age, location, building materials, building systems, amenities, lease rates, etc. Office buildings are of three classes: A, B, and C. **Class A** is generally the most desirable building, located in the most desirable locations, and offering first-rate design, building systems, and amenities. **Class B** buildings are located in good locations, have little chance of functional obsolescence, and have reasonable management. **Class C** buildings are typically older, have not been modernized, are often functionally obsolete, and may contain asbestos. These low standards make Class C buildings potential candidates for demolition or conversion to another use.

Size and Flexibility. Office buildings are typically grouped into three categories: **high rise** (16 stories and above), **mid rise** (four to 15 stories), and **low rise** (one to three stories).

Table 1 Data for U.S. Office Buildings

	Number of Buildings (Thousands)	Percent of Total Number of Buildings	Total Floor Space (Million m^2)	Percent of Total Floor Space
Total	824	100.0	1135	100.0
93 to 465 m^2	503	61.0	128	11.32
466 to 929 m^2	127	15.4	87	7.68
930 to 2323 m^2	116	14.1	175	15.46
2324 to 4647 m^2	43	5.2	140	12.34
4648 to 9264 m^2	17	2.1	112	9.90
9265 to 18 587 m^2	11	1.3	133	11.70
18 588 to 46 468 m^2	5	0.6	139	12.23
>46 468 m^2	2	0.2	220	19.37

Source: EIA (2003).

The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

Location. An office building is typically in one of three locations: **downtown** (usually high rises), **suburban** (low- to mid-rise buildings), or **business/industrial park** (typically one- to three-story buildings).

Floorplate (Floor Space Area). Size typically ranges from 1670 to 2800 m^2 and averages from 1860 to 2320 m^2.

Use and Ownership. Office buildings can be single tenant or multitenant. A single-tenant building can be owned by the tenant or leased from a landlord. From an HVAC&R systems standpoint, a single tenant/owner is more cautious considering issues such as life-cycle cost and energy conservation. In many cases, the systems are not selected based on the lowest first cost but on life-cycle cost. Sometimes, the developer may wish to select a system that allows individual tenants to pay directly for the energy they consume.

Building Features and Amenities. Examples typically include parking, telecommunications, HVAC&R, energy management, restaurants, security, retail outlets, and health club.

Typical areas that can be found in office buildings are

Offices

- Offices: (private or semiprivate acoustically and/or visually).
- Conference rooms

Employee/Visitor Support Spaces

- Convenience store, kiosk, or vending machines
- Lobby: central location for building directory, schedules, and general information
- Atria or common space: informal, multipurpose recreation and social gathering space
- Cafeteria or dining hall
- Private toilets or restrooms
- Child care centers
- Physical fitness area
- Interior or surface parking areas

Administrative Support Spaces

- May be private or semiprivate acoustically and/or visually.

Operation and Maintenance Spaces

- General storage: for items such as stationery, equipment, and instructional materials
- Food preparation area or kitchen
- Computer/information technology (IT) closets
- Maintenance closets
- Mechanical and electrical rooms

A well-designed and functioning HVAC system should provide the following:

- Comfortable and consistent temperature and humidity
- Adequate amounts of outdoor air at all time to satisfy ventilation requirements
- Remove odors and contaminates from circulated air

The major factors affecting sizing and selection of the HVAC systems are as follows:

- Building size, shape and number of floors
- Amount of exterior glass
- Orientation, envelope
- Internal loads, occupants, lighting
- Thermal zoning (number of zones, private offices, open areas, etc.)

Office HVAC systems generally range from small, unitary, decentralized cooling and heating up to large systems comprising central plants (chillers, cooling towers, boilers, etc.) and large air-handling systems. Often, several types of HVAC systems are applied in one building because of special requirements such as continuous operation, supplementary cooling, etc. In office buildings, the class of the building also affects selection of the HVAC systems. For example, in a class A office building, the HVAC&R systems must meet more stringent criteria, including individual thermal control, noise, and flexibility; HVAC systems such as single-zone constant-volume, water-source heat pump, and packaged terminal air conditioners (PTACs) might be inapplicable to this class, whereas properly designed variable-air-volume (VAV) systems can meet these requirements.

Design Criteria

A typical HVAC design criteria covers parameters required for thermal comfort, indoor air quality (IAQ), and sound. Thermal comfort parameters (temperature and humidity) are discussed in ASHRAE *Standard* 55-2010 and Chapter 9 of the 2017 *ASHRAE Handbook—Fundamentals*. Ventilation and IAQ are covered by ASHRAE *Standard* 62.1-2010, the user's manual for that standard (ASHRAE 2010), and Chapter 16 of the 2017 *ASHRAE Handbook—Fundamentals*. Sound and vibration are discussed in Chapter 49 of this volume and Chapter 8 of the 2017 *ASHRAE Handbook—Fundamentals.*

Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT), as well as nonenvironmental factors such as clothing, gender, age, and physical activity. These variables and how they correlate to thermal comfort can be evaluated by the *Thermal Comfort Tool CD* (ASHRAE 1997) in conjunction with ASHRAE *Standard* 55. General guidelines for temperature and humidity applicable for areas in office buildings are shown in Table 2.

All office, administration, and support areas need outdoor air for ventilation. Outdoor air is introduced to occupied areas and then exhausted by fans or exhaust openings, removing indoor air pollutants generated by occupants and any other building-related sources.

Table 2 Typical Recommended Indoor Temperature and Humidity in Office Buildings

Area	Indoor Design Conditions: Temperature, °C/ Relative Humidity, % — Winter	Summer	Comments
Offices, conference rooms, common areas	20.3 to 24.2 20 to 30%	23.3 to 26.7 50 to 60%	
Cafeteria	21.1 to 23.3 20 to 30%	25.8 50%	
Kitchen	21.1 to 23.3	28.9 to 31.1	No humidity control
Toilets	22.2		Usually not conditioned
Storage	17.8		No humidity control
Mechanical rooms	16.1		Usually not conditioned

ASHRAE *Standard* 62.1 is used as the basis for many building codes. To define the ventilation and exhaust design criteria, consult local applicable ventilation and exhaust standards. Table 3 provides recommendations for ventilation design based on the ventilation rate procedure method and filtration criteria for office buildings.

Acceptable noise levels in office buildings are important for office personnel; see Table 4 and Chapter 49.

Load Characteristics

Office buildings usually include both peripheral and interior zone spaces. The peripheral zone extends 3 to 3.6 m inward from the

Table 3 Typical Recommended Design Criteria for Ventilation and Filtration for Office Buildings

Category	Ventilation and Exhaust[a,b]: Combined Outdoor Air (Default Value) L/s per Person	Occupant Density,[f] per 100 m²	Outdoor Air: L/(s·m²)	Outdoor Air: L/s per Unit	Minimum Filtration Efficiency, MERV[c]
Office areas	8.5	5			6 to 8
Reception areas	3.5	30			6 to 8
Main entry lobbies	5.5	10			6 to 8
Telephone/data entry	3.0	60			6 to 8
Cafeteria	4.7	100			6 to 8
Kitchen[d,e]			3.5 (exhaust)		NA
Toilets				35 (exhaust)	NA
Storage[g]			0.6		1 to 4

Notes:
[a]Based on ASHRAE *Standard* 62.1-2010, Tables 6-1 and 6-4. For systems serving multiple zones, apply multiple-zone calculations procedure. If DCV is considered, see the section on Demand Control Ventilation (DCV).
[b]This table should not be used as the only source for design criteria. Governing local codes, design guidelines, ANSI/ASHRAE *Standard* 62.1-2010 and user's manual, (ASHRAE 2010) must be consulted.
[c]MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-2007.
[d]See Chapter 34 for additional information on kitchen ventilation. For kitchenette use 1.5 L/(s·m²).
[e]Consult local codes for kitchen exhaust requirements.
[f]Use default occupancy density when actual occupant density is not known.
[g]This recommendation for storage might not be sufficient when the materials stored have harmful emissions.

Table 4 Typical Recommended Design Guidelines for HVAC-Related Background Sound for Areas in Office Buildings

Category	Sound Criteria[a,b]: RC (N); QAI ≤ 5 dB	Comments
Executive and private office	25 to 35	
Conference rooms	25 to 35	
Teleconference rooms	≤25	
Open-plan office space	≤40 ≤35	 With sound masking
Corridors and lobbies	40 to 45	
Cafeteria	35 to 45	Based on service/support for hotels
Kitchen	35 to 45	Based on service/support for hotels
Storage	35 to 45	Based on service/support for hotels
Mechanical rooms	35 to 45	Based on service/support for hotels

Notes:
[a]Based on Table 1 in Chapter 49.
[b]RC (room criterion), QAI (quality assessment index) from Chapter 8 of the 2017 *ASHRAE Handbook—Fundamentals*.

outer wall toward the interior of the building, and frequently has a large window area. These zones may be extensively subdivided. Peripheral zones have variable loads because of changing sun position and weather. These zones typically require heating in winter. During intermediate seasons, one side of the building may require cooling, while another side requires heating. However, the interior zone spaces usually require a fairly uniform cooling rate throughout the year because their thermal loads are derived almost entirely from lights, office equipment, and people. Interior space conditioning is often by systems that have VAV control for low- or no-load conditions.

Most office buildings are occupied from approximately 8:00 AM to 6:00 PM; many are occupied by some personnel from as early as 5:30 AM to as late as 7:00 PM. Some tenants' operations may require night work schedules, usually not beyond 10:00 PM. Office buildings may contain printing facilities, information and computing centers, or broadcasting studios, which could operate 24 h per day. Therefore, for economical air-conditioning design, the intended uses of an office building must be well established before design development.

Occupancy varies considerably. In accounting or other sections where clerical work is done, the maximum density is approximately one person per 7 m^2 of floor area. Where there are private offices, the density may be as little as one person per 19 m^2. The most serious cases, however, are the occasional waiting rooms, conference rooms, or directors' rooms, where occupancy may be as high as one person per 2 m^2.

The lighting load in an office building can be a significant part of the total heat load. Lighting and normal equipment electrical loads average from 10 to 50 W/m^2 but may be considerably higher, depending on the type of lighting and amount of equipment. Buildings with computer systems and other electronic equipment can have electrical loads as high as 50 to 110 W/m^2. The amount, size, and type of computer equipment anticipated for the life of the building should be accurately appraised to size the air-handling equipment properly and provide for future installation of air-conditioning apparatus.

Total lighting heat output from recessed fixtures can be withdrawn by exhaust or return air and thus kept out of space-conditioning supply air requirements. By connecting a duct to each fixture, the most balanced air system can be provided. However, this method is expensive, so the suspended ceiling is often used as a return air plenum with air drawn from the space to above the suspended ceiling.

Miscellaneous allowances (for fan heat, duct heat pickup, duct leakage, and safety factors) should not exceed 12% of the total load.

Building shape and orientation are often determined by the building site, but some variations in these factors can increase refrigeration load. Shape and orientation should therefore be carefully analyzed in the early design stages.

Design Concepts

The variety of functions and range of design criteria applicable to office buildings have allowed the use of almost every available air-conditioning system. Multistory structures are discussed here, but the principles and criteria are similar for all sizes and shapes of office buildings.

Attention to detail is extremely important, especially in modular buildings. Each piece of equipment, duct and pipe connections, and the like may be duplicated hundreds of times. Thus, seemingly minor design variations may substantially affect construction and operating costs. In initial design, each component must be analyzed not only as an entity, but also as part of an integrated system. This systems design approach is essential for achieving optimum results.

As discussed under General Design Considerations, there are several classes of office buildings, determined by the type of financing required and the tenants who will occupy the building. Design evaluation may vary considerably based on specific tenant requirements; it is not enough to consider typical floor patterns only. Many larger office buildings include stores, restaurants, recreational facilities, data centers, telecommunication centers, radio and television studios, and observation decks.

Built-in system flexibility is essential for office building design. Business office procedures are constantly being revised, and basic building services should be able to meet changing tenant needs.

The type of occupancy may have an important bearing on air distribution system selection. For buildings with one owner or lessee, operations may be defined clearly enough that a system can be designed without the degree of flexibility needed for a less well-defined operation. However, owner-occupied buildings may require considerable design flexibility because the owner will pay for all alterations. The speculative builder can generally charge alterations to tenants. When different tenants occupy different floors, or even parts of the same floor, the degree of design and operation complexity increases to ensure proper environmental comfort conditions to any tenant, group of tenants, or all tenants at once. This problem is more acute if tenants have seasonal and variable overtime schedules.

Certain areas may have hours of occupancy or design criteria that differ substantially from those of the office administration areas; such areas should have their own air distribution systems and, in some cases, their own heating and/or refrigeration equipment.

Main entrances and lobbies are sometimes served by a separate and self contained system because they buffer the outdoor atmosphere and the building interior. Some engineers prefer to have a lobby summer temperature 2 to 3.5 K above office temperature to reduce operating cost and temperature shock to people entering or leaving the building. In cases where lobbies or main entrances have longer (or constant) operation, a dedicated/self-contained HVAC system is recommended to allow turning off other building systems.

The unique temperature and humidity requirements of server rooms or computer equipment/data processing installations, and the fact that they often run 24 h per day for extended periods, generally warrant separate refrigeration and air distribution systems. Separate back-up systems may be required for data processing areas in case the main building HVAC system fails. Chapter 20 has further information.

The degree of air filtration required should be determined. Service cost and effect of air resistance on energy costs should be analyzed for various types of filters. Initial filter cost and air pollution characteristics also need to be considered. Activated charcoal filters for odor control and reduction of outdoor air requirements are another option to consider.

Providing office buildings with continuous 100% outdoor air (OA) is seldom justified, so most office buildings are designed to minimize outdoor air use, except during economizer operation. However, attention to indoor air quality may dictate higher levels of ventilation air. In addition, the minimum volume of outdoor air should be maintained in variable-volume air-handling systems. Dry-bulb- or enthalpy-controlled economizer cycles should be considered for reducing energy costs. Consult ASHRAE *Standard* 90.1-2010 for the proper air economizer system (dry-bulb or enthalpy). When an economizer cycle is used, systems should be zoned so that energy is not wasted by heating outdoor air. This is often accomplished by a separate air distribution system for the interior and each major exterior zone. A dedicated outdoor air system (DOAS) can be considered where the zones are served by in-room terminal systems (fan coils, induction unit systems, etc.) or decentralized systems [e.g., minisplit HVAC, water-source heat pump (WSHP)]. Because the outdoor air supply is relatively low in office buildings, air-to-air heat recovery is not cost effective; instead, a DOAS with enhanced cooling and dehumidification systems can be used.

These systems typically use hot-gas reheat or other means of free reheat (e.g., heat pipes, plate-frame heat exchangers). In hot, humid climates, these systems can significantly improve space conditions. By having a DOAS, the OA supply can be turned off during unoccupied hours (which can be significant in office buildings). In unoccupied mode, the in-room unit needs to maintain only the desired space conditions (e.g., night/weekend setback temperature).

High-rise office buildings have traditionally used perimeter fan-powered VAV terminals, induction, or fan-coil systems. Separate all-air systems have generally been used for the interior and/or the exterior for the fan-powered VAV perimeter terminals; modulated air diffusers and fan-powered perimeter unit systems have also been used. If variable-air-volume systems serve the interior, perimeters are usually served by variable-volume fan-powered terminals, typically equipped with hydronic (hot-water) or electric reheat coils. In colder climates, perimeter baseboard heaters are commonly applied. Baseboards are typically installed under windows to minimize the effect of the cold surface.

Many office buildings without an economizer cycle have a bypass multizone unit installed on each floor or several floors with a heating coil in each exterior zone duct. VAV variations of the bypass multizone and other floor-by-floor, all-air, or self-contained systems are also used. These systems are popular because of their low fan power and initial cost, and the energy savings possible from independent operating schedules between floors occupied by tenants with different operating hours.

Perimeter radiation or infrared systems with conventional, single-duct, low-velocity air conditioning that furnishes air from packaged air-conditioning units may be more economical for small office buildings. The need for a perimeter system, which is a function of exterior glass percentage, external wall thermal value, and climate severity, should be carefully analyzed.

A perimeter heating system separate from the cooling system is preferable, because air distribution devices can then be selected for a specific duty rather than as a compromise between heating and cooling performance. The higher cost of additional air-handling or fan-coil units and ductwork may lead the designer to a less expensive option, such as fan-powered terminal units with heating coils serving perimeter zones in lieu of a separate heating system. Radiant ceiling panels for perimeter zones are another option.

Interior space use usually requires that interior air-conditioning systems allow modification to handle all load situations. Variable-air-volume systems are often used. When using these systems, low-load conditions should be carefully evaluated to determine whether adequate air movement and outdoor air can be provided at the proposed supply air temperature without overcooling. Increases in supply air temperature tend to nullify energy savings in fan power, which are characteristic of VAV systems. Low-temperature air distribution for additional savings in transport energy is seeing increased use, especially when coupled with an ice storage system.

In small to medium-sized office buildings, air-source heat pumps or minisplit systems (cooling only, heat pump, or combination) such as variable refrigerant flow (VRF) may be chosen. VRF systems that can cool and heat simultaneously are available and allow users to provide heating in perimeter zones and cooling in interior zones in a similar fashion to four-pipe fan coil (FPFC) systems. In larger buildings, water-source heat pump (WSHP) systems are feasible with most types of air-conditioning systems. Heat removed from core areas is rejected to either a cooling tower or perimeter circuits. The water-source heat pump can be supplemented by a central heating system or electrical coils on extremely cold days or over extended periods of limited occupancy. Removed excess heat may also be stored in hot-water tanks. Note that in-room systems (e.g., VRF, WSHP) might need a DOAS to provide the required outdoor air.

Many heat recovery or water-source heat pump systems exhaust air from conditioned spaces through lighting fixtures. This reduces required air quantities and extends lamp life by providing a much cooler ambient operating environment.

Suspended-ceiling return air plenums eliminate sheet metal return air ductwork to reduce floor-to-floor height requirements. However, suspended-ceiling plenums may increase the difficulty of proper air balancing throughout the building. Problems often connected with suspended ceiling return plenums include

- Air leakage through cracks, with resulting smudges
- Tendency of return air openings nearest to a shaft opening or collector duct to pull too much air, thus creating uneven air motion and possible noise
- Noise transmission between office spaces

Air leakage can be minimized by proper workmanship. To overcome drawing too much air, return air ducts can be run in the suspended ceiling pathway from the shaft, often in a simple radial pattern. Ends of ducts can be left open or dampered. Generous sizing of return air grilles and passages lowers the percentage of circuit resistance attributable to the return air path. This bolsters effectiveness of supply-air-balancing devices and reduces the significance of air leakage and drawing too much air. Structural blockage can be solved by locating openings in beams or partitions with fire dampers, where required.

Systems and Equipment Selection

Selection of HVAC equipment and systems depends on whether the facility is new or existing, and whether it is to be totally or partially renovated. For minor renovations, existing HVAC systems are often expanded in compliance with current codes and standards with equipment that matches the existing types. For major renovations or new construction, new HVAC systems and equipment should be installed. When applicable, the remaining useful life of existing equipment and distribution systems should be considered.

HVAC systems and equipment energy use and associated life cycle costs should be evaluated. Energy analysis may justify new HVAC equipment and systems when an acceptable return on investment can be shown. The engineer must review all assumptions in the energy analysis with the owner. Other considerations for existing facilities are (1) whether the central plant is of adequate capacity to handle additional loads from new or renovated facilities; (2) age and condition of existing equipment, pipes, and controls; and (3) capital and operating costs of new equipment.

Chapter 1 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* provides general guidelines on HVAC systems analysis and selection procedures. Although in many cases system selection is based solely on the lowest first cost, it is suggested that the engineer propose a system with the lowest life-cycle cost (LCC). LCC analysis typically requires hour-by-hour building energy simulation for annual energy cost estimation. Detailed first and maintenance cost estimates of proposed design alternatives, using sources such as R.S. Means (R.S. Means 2010a, 2010b), can also be used for the LCC analysis along with software such as BLCC 5.1 (FEMP 2003). Refer to Chapters 38 and 60 and the Value Engineering and Life-Cycle Cost Analysis section of this chapter for additional information.

System Types. HVAC systems for office buildings may be centralized, decentralized, or a combination of both. Centralized systems typically incorporate secondary systems to treat the air and distribute it. The cooling and heating medium is typically water or brine that is cooled and/or heated in a primary system and distributed to the secondary systems. Centralized systems comprise the following systems:

Secondary Systems

- Air handling and distribution (see Chapter 4 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

- In-room terminal systems (see Chapter 5 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Dedicated outdoor air systems (DOAS) with chilled water for cooling and hot water, steam, or electric heat for heating (for special areas when required)

Primary Systems

- Central cooling and heating plant (see Chapter 3 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

More detailed information on systems selection by application can be found in Table 5.

Typical decentralized systems (dedicated systems serving a single zone, or packaged systems such as packaged variable air volume) include the following:

- Water-source heat pumps (WSHP), also known as water-loop heat pumps (WLHP)
- Geothermal heat pumps (e.g., groundwater heat pumps, ground-coupled heat pumps)
- Hybrid geothermal heat pumps (combination of groundwater heat pumps, ground-coupled heat pumps, and an additional heat rejection device) for cases with limited area for the ground-coupled heat exchanger or where it is economically justified
- Packaged single-zone and variable-volume units
- Light commercial split systems
- Minisplit and variable refrigerant flow (VRF) units

Chapters 2, 9, 49, and 50 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* provide additional information on decentralized HVAC systems. Additional information on geothermal energy can be found in Chapter 35 of this volume.

Whereas small office buildings (<2320 m^2) normally apply packaged unitary and split systems equipment, larger office buildings can use a combination of packaged, unitary, split, and/or centralized systems, or large packaged rooftop systems. The building class also must be considered during system selection.

Systems Selection by Application. Table 5 shows the applicability of several systems for office buildings.

Special Systems

The following is a list of systems that can be considered for special areas in office buildings. Chapter 58 of this volume, Chapter 6 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*, and Skistad et al. (2002) provide additional information of these systems.

- Displacement ventilation
- Underfloor air distribution (UFAD)
- Active (induction) and passive chilled beams

Demand-Controlled Ventilation (DCV). Demand-controlled ventilation can reduce the operating cost of HVAC systems. Areas such as auditoriums, large conference rooms, and other spaces designed for large numbers of occupants and intermittent occupancy can use DCV. This approach is most cost effective when one dedicated air handling system serves each of these zones. Special attention is required when DCV is applied to VAV systems. In these cases, it is insufficient to use only one CO_2 sensor in the return air plenum of the central AHU, because the readings are the average of all the zones. To address properly DCV in a VAV system, a CO_2 sensor is required in every controlled zone.

Spatial Requirements

Total office building electromechanical space requirements vary tremendously based on types of systems planned; however, the average is approximately 8 to 10% of the gross area. Clear height required for fan rooms varies from approximately 3 to 5.5 m, depending on the distribution system and equipment complexity. On office floors, perimeter fan-coil or induction units require approximately 1 to 3% of the floor area. Interior air shafts and pipe chases require approximately 3 to 5% of the floor area. Therefore, ducts, pipes, and equipment require approximately 4 to 8% of each floor's gross area.

Where large central units supply multiple floors, shaft space requirements depend on the number of fan rooms. In such cases, one mechanical equipment room usually furnishes air requirements for 8 to 20 floors (above and below for intermediate levels), with an average of 12 floors. The more floors served, the larger the duct shafts and equipment required. This results in higher fan room heights and greater equipment size and mass.

The fewer floors served by an equipment room, the greater the flexibility in serving changing floor or tenant requirements. Often, one mechanical equipment room per floor and complete elimination of vertical shafts requires no more total floor area than fewer larger mechanical equipment rooms, especially when there are many small rooms and they are the same height as typical floors. Equipment can also be smaller, although maintenance costs are higher. Energy costs may be reduced with more equipment rooms serving fewer areas, because equipment can be shut off in unoccupied areas, and high-pressure ductwork is not required. Equipment rooms on upper levels generally cost more to install because of rigging and transportation logistics.

In all cases, mechanical equipment rooms must be thermally and acoustically isolated from office areas.

Cooling Towers. Cooling towers can be the largest single piece of equipment required for air-conditioning systems. Cooling towers require approximately 1 m^2 of floor area per 400 m^2 of total building area and are 4 to 12 m high. If towers are located on the roof, the building structure must be able to support the cooling tower and dunnage, full water load (approximately 590 to 730 kg/m^2), and seismic and wind load stresses.

Where cooling tower noise may affect neighboring buildings, tower design should include sound traps or other suitable noise baffles. This may affect tower space, mass of the units, and motor

Table 5 Applicability of Systems to Typical Office Buildings

	Cooling/Heating Systems							Heating Only	
	Centralized			Decentralized					
Building Area/Stories	SZ[a]	VAV/ Reheat	Fan Coil (Two-and Four-Pipe)	PSZ/SZ*/ Split/ VRF	PVAV/ Reheat	WSHP	Geothermal Heat Pump and Hybrid Geothermal Heat Pump	Perimeter Baseboard/ Radiators	Unit Heaters
<2320 m^2, one to three stories				X		X	X	X	Special areas
2230 to 13 940 m^2, one to five stories	X	X	X	X	X	X	X	X	Special areas
>13 940 m^2, low rise and high rise	X	X	X			X	X	X	Special areas

*SZ = single zone
VAV = variable-air-volume
PSZ = packaged single zone
PVAV = packaged variable-air-volume
WSHP = water-source heat pump
VRF = variable refrigerant flow

power. Slightly oversizing cooling towers can reduce noise and power consumption because of lower speeds and also the ability to reduce the condenser water temperature, which reduces cooling energy. The size increase may increase initial cost.

Cooling towers are sometimes enclosed in a decorative screen for aesthetic reasons; therefore, calculations should ascertain that the screen has sufficient free area for the tower to obtain its required air quantity and to prevent recirculation.

If the tower is placed in a rooftop well or near a wall, or split into several towers at various locations, design becomes more complicated, and initial and operating costs increase substantially. Also, towers should not be split and placed on different levels because hydraulic problems increase. Finally, the cooling tower should be built high enough above the roof so that the bottom of the tower and the roof can be maintained properly.

Special Considerations

Office building areas with special ventilation and cooling requirements include elevator machine rooms, electrical and telephone closets, electrical switchgear, plumbing rooms, refrigeration rooms, and mechanical equipment rooms. The high heat loads in some of these rooms may require air-conditioning units for spot cooling.

In larger buildings with intermediate elevator, mechanical, and electrical machine rooms, it is desirable to have these rooms on the same level or possibly on two levels. This may simplify horizontal ductwork, piping, and conduit distribution systems and allow more effective ventilation and maintenance of these equipment rooms.

An air-conditioning system cannot prevent occupants at the perimeter from feeling direct sunlight. Venetian blinds and drapes are often provided but seldom used. External shading devices (screens, overhangs, etc.) or reflective glass are preferable.

Tall buildings in cold climates experience severe stack effect. The extra amount of heat provided by the air-conditioning system in attempts to overcome this problem can be substantial. The following features help combat infiltration from stack effect:

- Revolving doors or vestibules at exterior entrances
- Pressurized lobbies or lower floors
- Tight gaskets on stairwell doors leading to the roof
- Automatic dampers on elevator shaft vents
- Tight construction of the exterior skin
- Tight closure and seals on all dampers opening to the exterior

2. TRANSPORTATION CENTERS

Major transportation facilities include transit facilities (rail transit, bus terminals), airports, and cruise terminals. Other areas that can be found in transportation centers are airplane hangars and freight and mail buildings, which can be treated as warehouse facilities. Bus terminals are covered partially in this chapter, but Chapter 16 provides more detail.

Airports

Airports are large, complex, and highly profitable enterprise. Most U.S. airports are public nonprofits, run directly by government entities or by government-created authorities known as airport or port authorities. There are three main types of airports:

- **International airports** serving over 20 million passengers a year.
- **National airports** serving between 2 to 20 million passengers a year.
- **Regional airport** serving up to 2 million passengers a year.

Airports typically consists the following:

- Runways and taxiing areas
- Air traffic control buildings
- Aircraft maintenance buildings and hangars
- Passenger terminals and car parking (open, partially open, or totally enclosed)
- Freight warehouses
- Lodging facilities (hotels)

In addition, support areas such as administration buildings, central utility plants, and transit facilities (rail and bus) are common in airport facilities.

Areas such as hangars, hotels, and car parking are not covered in this section. Information about hotels and parking garages can be found in Chapters 7 and 16, respectively. Warehouses are discussed in the next section of this chapter.

Most terminals can be divided into the following sections and subsections:

Departure

- Entrance concourse
- Check-in and ticketing
- Security and passports
- Shops, restaurants, banks, medical services, conference and business facilities, etc.
- Departure lounge
- Departure gates

Arrival

- Arrival lounge
- Baggage claim
- Customs, immigration, and passport control
- Exit concourse

Cruise Terminals

Cruise terminals typically have three main areas: departure/arrival concourse, ticketing, and baggage handling. These areas are open and large, and are designed to provide acceptable thermal comfort to the passenger during embarkation and debarkation.

Design Criteria

Transportation centers consist of a variety of areas, such as administration, large open areas, shops, and restaurants. Design criteria for these areas should be based on information on relevant chapters from this volume or ASHRAE *Standard* 62.1.

Load Characteristics

Airports, cruise terminals, and bus terminals operate on a 24 h basis, with a reduced schedule during late night and early morning hours. To better understand the load characteristics of these facilities, computer-based building energy modeling and simulation tools should be used; this chapter provides basic information and references for energy modeling. Given the dynamic nature of transportation facilities, well-supported assumptions of occupancy schedules should be established during the analysis process.

Airports. Terminal buildings consist of large, open circulating areas, one or more floors high, often with high ceilings, ticketing counters, and various types of stores, concessions, and convenience facilities. Lighting and equipment loads are generally average, but occupancy varies substantially. Exterior loads are, of course, a function of architectural design. The largest single problem often is thermal drafts created by large entranceways, high ceilings, and long passageways that have openings to the outdoors.

Cruise Terminals. Freight and passenger docks consist of large, high-ceilinged structures with separate areas for administration, visitors, passengers, cargo storage, and work. The floor of the dock is usually exposed to the outdoors just above the water level. Portions of the sidewalls are often open while ships are in port. In addition, the large ceiling (roof) area presents a large heating and cooling load. Load characteristics of passenger dock terminals generally require roof and floors to be well insulated. Occasional heavy occupancy loads in visitor and passenger areas must be considered.

Bus Terminals. These buildings consist of two general areas: the terminal, which contains passenger circulation, ticket booths, and stores or concessions; and the bus loading area. Waiting rooms and passenger concourse areas are subject to a highly variable occupant load: density may reach 1 m^2 per person and, at extreme periods, 0.3 to 0.5 m^2 per person. Chapter 16 has further information on bus terminals.

Design Concepts

Heating and cooling is generally centralized or provided for each building or group in a complex. In large, open-circulation areas of transportation centers, any all-air system with zone control can be used. Where ceilings are high, air distribution is often along the side wall to concentrate air conditioning where desired and avoid disturbing stratified air. Perimeter areas may require heating by radiation, a fan-coil system, or hot air blown up from the sill or floor grilles, particularly in colder climates. Hydronic perimeter radiant ceiling panels may be especially suited to these high-load areas.

Airports. Airports generally consist of one or more central terminal buildings connected by long passageways or trains to rotundas containing departure lounges for airplane loading. Most terminals have portable telescoping-type loading bridges connecting departure lounges to the airplanes. These passageways eliminate heating and cooling problems associated with traditional permanent passenger-loading structures.

Because of difficulties in controlling the air balance and because of the many outdoor openings, high ceilings, and long, low passageways (which often are not air conditioned), the terminal building (usually air conditioned) should be designed to maintain a substantial positive pressure. Zoning is generally required in passenger waiting areas, in departure lounges, and at ticket counters to take care of the widely variable occupancy loads.

Main entrances may have vestibules and windbreaker partitions to minimize undesirable air currents in the building.

Hangars must be heated in cold weather, and ventilation may be required to eliminate possible fumes (although fueling is seldom permitted in hangars). Gas-fired, electric, and low- and high-intensity radiant heaters are used extensively in hangars because they provide comfort for employees at relatively low operating costs.

Hangars may also be heated by large air blast heaters or floor-buried heated liquid coils. Local exhaust air systems may be used to evacuate fumes and odors that occur in smaller ducted systems. Under some conditions, exhaust systems may be portable and may include odor-absorbing devices.

Cruise Terminals. In severe climates, occupied floor areas may contain heated floor panels. The roof should be well insulated, and, in appropriate climates, evaporative spray cooling substantially reduces the summer load. Freight docks are usually heated and well ventilated but seldom cooled.

High ceilings and openings to the outdoors may present serious draft problems unless the systems are designed properly. Vestibule entrances or air curtains help minimize cross drafts. Air door blast heaters at cargo opening areas may be quite effective.

Ventilation of the dock terminal should prevent noxious fumes and odors from reaching occupied areas. Therefore, occupied areas should be under positive pressure and cargo and storage areas exhausted to maintain negative air pressure. Occupied areas should be enclosed to simplify any local air conditioning.

In many respects, these are among the most difficult buildings to heat and cool because of their large open areas. If each function is properly enclosed, any commonly used all-air or large fan-coil system is suitable. If areas are left largely open, the best approach is to concentrate on proper building design and heating and cooling of the openings. High-intensity infrared spot heating is often advantageous (see Chapter 16 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*). Exhaust ventilation from tow truck and cargo areas should be exhausted through the roof of the dock terminal.

Bus Terminals. Conditions are similar to those for airport terminals, except that all-air systems are more practical because ceiling heights are often lower, and perimeters are usually flanked by stores or office areas. The same systems are applicable as for airport terminals, but ceiling air distribution is generally feasible.

Properly designed radiant hydronic or electric ceiling systems may be used if high-occupancy latent loads are fully considered. This may result in smaller duct sizes than are required for all-air systems and may be advantageous where bus-loading areas are above the terminal and require structural beams. This heating and cooling system reduces the volume of the building that must be conditioned. In areas where latent load is a concern, heating-only panels may be used at the perimeter, with a cooling-only interior system.

The terminal area air supply system should be under high positive pressure to ensure that no fumes and odors infiltrate from bus areas. Positive exhaust from bus loading areas is essential for a properly operating total system (see Chapter 16).

Systems and Equipment Selection

Given the size and magnitude of the systems in airports and cruise terminals, the selection of the HVAC equipment and systems tend to be centralized. Depending on the area served and site limitations, decentralized systems can also be considered for these specific cases.

Centralized systems typically incorporate secondary systems to treat and distribute air. The cooling and heating medium is typically water or brine that is cooled and/or heated in a primary system and distributed to the secondary systems. Centralized systems comprise the following systems:

Secondary Systems

- Air handling and distribution (see Chapter 4 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)
- In-room terminal systems (see Chapter 5 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Secondary systems such as variable air volume (VAV) are common in airports. Small, single-zone areas can be treated by constant-volume systems or fan coils.

Primary Systems

- Central cooling and heating plant (see Chapter 3 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)
- For cases where decentralized systems (dedicated systems serving a single zone or packaged systems such as packaged variable air volume) are:
- Water-source heat pumps (WSHP) (also known as water-loop heat pumps or WLHP)
- Packaged single-zone and variable-volume units
- Light commercial split systems
- Mini-split and variable-refrigerant-flow (VRF) units

Special Considerations

Airports. Filtering outdoor air with activated charcoal filters should be considered for areas subject to excessive noxious fumes from jet engine exhausts. However, locating outdoor air intakes as remotely as possible from airplanes is a less expensive and more positive approach.

Where ionization filtration enhancers are used, outdoor air quantities are sometimes reduced because the air is cleaner. However, care must be taken to maintain sufficient amounts of outdoor air for space pressurization.

Cruise Terminals. Ventilation design must ensure that fumes and odors from forklifts and cargo in work areas do not penetrate occupied and administrative areas.

Bus Terminals. The primary concerns with enclosed bus loading areas are health and safety problems, which must be handled by proper ventilation (see Chapter 16). Although diesel engine fumes are generally not as noxious as gasoline fumes, bus terminals often have many buses loading and unloading at the same time, and the total amount of fumes and odors may be disturbing.

In terms of health and safety, enclosed bus loading areas and automobile parking garages present the most serious problems. Three major problems are encountered, the first and most serious of which is emission of carbon monoxide (CO) by cars and oxides of nitrogen (NO_x) by buses, which can cause serious illness and possibly death. Oil and gasoline fumes, which may cause nausea and headaches and can create a fire hazard, are also of concern. The third issue is lack of air movement and the resulting stale atmosphere caused by increased CO content in the air. This condition may cause headaches or grogginess. Most codes require a minimum ventilation rate to ensure that the CO concentration does not exceed safe limits. Chapter 16 covers ventilation requirements and calculation procedures for enclosed vehicular facilities in detail.

All underground garages should have facilities for testing the CO concentration or should have the garage checked periodically. Problems such as clogged duct systems; improperly operating fans, motors, or dampers; or clogged air intake or exhaust louvers may not allow proper air circulation. Proper maintenance is required to minimize any operational defects.

3. WAREHOUSES AND DISTRIBUTION CENTERS

General Design Considerations

Warehouses can be defined as facilities that provide proper environment for the purpose of storing goods and materials. They are also used to store equipment and material inventory at industrial facilities. At times, warehouses may be open to the public. The buildings are generally not air conditioned, but often have sufficient heat and ventilation to provide a tolerable working environment. In many cases, associated facilities occupied by office workers, such as shipping, receiving, and inventory control offices, are air conditioned. Warehouses must be designed to accommodate the loads of materials to be stored, associated handling equipment, receiving and shipping operations and associated trucking, and needs of operating personnel. Types of warehouses include the following:

- **Heated and unheated general warehouses** provide space for bulk, rack, and bin storage, aisle space, receiving and shipping space, packing and crating space, and office and toilet space. As indicated some areas are typically equipped with small-decentralized air-conditioning systems for the support personnel.
- **Conditioned general warehouses** are similar to heated and unheated general warehouses, but can provide space cooling to meet the stored goods' requirements.
- **Refrigerated warehouses** are designed to preserve the quality of perishable goods and general supply materials that require refrigeration. This includes freeze and chill spaces, processing facilities, and mechanical areas. For information on this type of warehouse, see Chapters 23 and 24 in the 2018 *ASHRAE Handbook—Refrigeration*.
- **Controlled humidity (CH) and dry-air storage warehouses** are similar to general warehouses except that they are constructed with vapor barriers and contain humidity control equipment to maintain humidity at desired levels. For additional information, see Chapter 29 of Harriman et al. (2001).
- **Specialty warehouses** includes storing facilities with special and in some instances strict requirements for temperature, humidity, cleanliness, minimum ventilation rates, etc. These facilities are typically conditioned to achieve the required space conditions. These warehouses can be found in industrial and manufacturing facilities or can be standalone buildings. Examples include
  - Pharmaceutical and life sciences facilities. Good manufacturing practices (GMP) may be required.
  - Liquid storage (fuel and nonpropellants), flammable and combustible storage, radioactive material storage, hazardous chemical storage, and ammunition storage.
  - Automated storage and retrieval systems (AS/RS), which are designed for maximum storage and minimum personnel on site. They are built for lower-temperature operation with minimal heat and light needed, but require a tall structure with extremely level floors. In some cases, specialty HVAC equipment is required for servers and other computer areas in AS/RS facility.

Features already now common in warehouse designs are higher bays, sophisticated materials-handling equipment, broadband connectivity access, and more distribution networks. A wide range of storage alternatives, picking alternatives, material-handling equipment, and software exist to meet the physical and operational requirements. Warehouse spaces must also be flexible to accommodate future operations and storage needs as well as mission changes.

Areas that can be found in warehouses and distribution centers include the following:

- Storage areas
- Office and administrative areas
- Loading docks
- Light industrial spaces
- Computer/server rooms

Other areas can be site specific.

Design Criteria

Design criteria (temperature, humidity, noise, etc.) for warehouses are space specific; the designer should refer to the relevant sections and chapters (e.g., the section on Office Buildings for office and administration areas). For conditioned storage areas, the special requirements of the product stores dictate the design conditions.

Outdoor air for ventilation of office, administration, and support areas should be based on local code requirements or ASHRAE *Standard* 62.1. For general warehouses where special ventilation or minimum ventilation rates are not specifically defined, *Standard* 62.1 can be used as the criterion for minimum outdoor air. To define the specific ventilation and exhaust design criteria, consult local applicable ventilation and exhaust standards. Table 6-1 of *Standard* 62.1 recommends 0.3 $L/(s \cdot m^2)$ of ventilation as a design criterion for warehouse ventilation, although this amount may be insufficient when stored materials have harmful emissions.

Load Characteristics

Given the variety of warehouses facilities, every case should be analyzed carefully. In general, internal loads from lighting, people, and miscellaneous sources are low. Most of the load is thermal transmission and infiltration. An air-conditioning load profile tends to flatten where materials stored are massive enough to cause the peak load to lag. In humid climates, special attention should be given to the sensible and latent loads' variations for cases where the warehouse or distribution center is conditioned or cooled by thermostatically controlled packaged HVAC equipment. In these climates, it is common to satisfy the space temperature (i.e., very low or no sensible cooling load), but, because of infiltration of moist air and without proper cooling (i.e., the cooling equipment is off), for space humidity to be unacceptably high.

Design Concepts

Most warehouses are only heated and ventilated. Forced-flow unit heaters may be located near entrances and work areas. Large central heating and ventilating units are also widely used. Even though comfort for warehouse workers may not be considered, it may be necessary to keep the temperature above 4°C to protect sprinkler piping or stored materials from freezing.

A building designed for adding air conditioning at a later date requires less heating and is more comfortable. For maximum summer comfort without air conditioning, excellent ventilation with noticeable air movement in work areas is necessary. Even greater comfort can be achieved in appropriate climates by adding roof-spray cooling. This can reduce the roof's surface temperature, thereby reducing ceiling radiation inside. Low- and high-intensity radiant heaters can be used to maintain the minimum ambient temperature throughout a facility above freezing. Radiant heat may also be used for occupant comfort in areas permanently or frequently open to the outdoors.

If the stored product requires specific inside conditions, an air-conditioning system must be added. Using only ventilation may help maintain lower space temperatures, but care should be taken not to damage the stored product with uncontrolled humidity. Direct or indirect evaporative cooling may also be an option.

Systems and Equipment Selection

Selection of HVAC equipment and systems depends on type of warehouse. As indicated previously, the warehouse might need only heating/cooling in admin areas, or in some cases, highly sophisticated HVAC systems to address special ambient conditions required by the product stored in this warehouse. The same principles and procedures of selecting the HVAC systems described in the office building section of this chapter should be followed.

Selection by Application. Table 6 depicts typical systems applied for warehouse facilities. Centralized systems refer to warehouses where central chilled-water and/or hot-water/steam system is available. Decentralized systems are typically direct expansion (DX) systems with gas-fired heating or other available heating source.

Special systems are typically required when special ambient conditions have to be maintained: usual examples are desiccant dehumidification, mechanical dehumidification, and humidification.

In hot and humid climates, a combination of desiccant-based dehumidification equipment along with standard DX, packaged, single-zone units can be considered. This approach allows separation of sensible cooling load from latent load, thereby enhancing humidity control under most ambient conditions, reducing energy consumption, and allowing optimal equipment sizing and use.

Table 6 Applicability of Systems to Typical Warehouse Building Areas

	Cooling/Heating Systems		Heating Only	
	Centralized	Decentralized		
Warehouse Area	SZ	PSZ/SZ Split/VRF	Heating and Ventilating Units	Local Unit Heaters
Storage areas	X	X	X	X
Office and administration areas	X	X		
Loading docks			X	X
Light industrial spaces	X	X	X	
Computer/server rooms	X (also CHW, CRAC Unit)	X (also DX, CRAC Unit)		

SZ = single zone
PSZ = packaged single zone
VRF = variable refrigerant flow
CHW = chilled water
CRAC = computer room air conditioning

Spatial Requirements

Total building electromechanical space requirements vary based on types of systems planned. Typically, the HVAC equipment can be roof mounted, slab, indoor, or ceiling mounted. Ductwork and air discharge plenums usually are not concealed; often, the systems are free discharge.

Special Considerations

Forklifts and trucks powered by gasoline, propane, and other fuels are often used inside warehouses. Proper ventilation is necessary to alleviate build-up of CO and other noxious fumes. Proper ventilation of battery-charging rooms for electrically powered forklifts and trucks is also required.

4. SUSTAINABILITY AND ENERGY EFFICIENCY

In the context of this chapter, sustainable refers to a building that minimizes the use of energy, water, and other natural resources and provides a healthy and productive indoor environment (e.g., IAQ, lighting, noise). The HVAC&R designer plays a major role in supporting the design team in designing, demonstrating, and verifying these goals, particularly in the areas of energy efficiency and indoor environmental quality (mainly IAQ).

Several tools and mechanisms are available to assist the HVAC&R designer in designing and demonstrating sustainable commercial facilities; see the References and Bibliography in this chapter, the Sustainability and Energy Efficiency section in Chapter 8, and Chapter 35 in the 2017 *ASHRAE Handbook—Fundamentals*.

Energy Considerations

Energy standards such as ANSI/ASHRAE/IESNA *Standard* 90.1-2007 and local energy codes should be followed for minimum energy conservation criteria. Note that additional aspects such as lighting, motors/drives, building envelope, and electrical services should also be considered for energy reduction. Energy procurement/supply-side opportunities should also be investigated for energy cost reduction. Table 14 in Chapter 8 depicts a list of selected energy conservation opportunities.

Energy Efficiency and Integrated Design Process for Commercial Facilities

The integrated design process (IDP) is vital for the design of high-performance commercial facilities. For background and details on integrated building design (IBD) and IDP, see Chapter 60.

Unlike the sequential design process (SDP), where the elements of the built solution are defined and developed in a systematic and sequential manner, IDP encourages holistic collaboration of the project team during the all phases of the project, resulting in cost-effective and environmentally friendly design. IDP responds to the project objectives, which typically are established by the owner before team selection. Typical IDP includes the following elements:

- Owner planning
- Predesign
- Schematic design
- Schematic design
- Design development
- Construction documents
- Procurement
- Construction
- Operation

Detailed information on each element can be found in Chapter 60.

In high-performance buildings, these objectives are typically sustainable sites, water efficiency, energy and atmosphere quality, materials and resources, and indoor environmental quality. These objectives are the main components of several rating systems. Energy use objectives are typically the following:

- Meeting minimum prescriptive compliance (mainly local energy codes, ASHRAE *Standard* 90.1, etc.)
- Improving energy performance by an owner-defined percentage beyond the applicable code benchmark
- Demonstrating minimum energy performance (or prerequisite) and enhanced energy efficiency (for credit points) for sustainable design rating [e.g., U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED®)]
- Providing a facility/building site energy density [e.g., energy utilization index (EUI)] less than an owner-defined target [e.g., U.S. Environmental Protection Agency (EPA) ENERGY STAR guidelines)
- Provide an owner-defined percentage of facility source energy from renewable energy

Building Energy Modeling

Building energy modeling has been one of the most important tools in the process of IDP and sustainable design. Building energy modeling uses sophisticated methods and tools to estimate the energy consumption and behavior of buildings and building systems. To better illustrate the concept of energy modeling, the difference between HVAC sizing and selection programs and energy modeling tools will be described.

Design, sizing selection, and equipment sizing tools are typically used for design and sizing of HVAC&R systems, normally at the **design** process. Examples include cooling/heating load calculations tools, ductwork design software, piping design programs, acoustics software, and selection programs for specific types of equipment. The results are used to specify cooling and heating capacities, airflow, water flow, equipment size, etc., during the design as defined and agreed by the client.

Energy modeling [also known as building modeling and simulation (BMS)] is used to model the building's thermal behavior and the building energy systems' performance. Unlike design tools, which are used for one design point (or for sizing), the building energy simulation analyzes the building and the building systems up to 8760 times: hour by hour, or even in smaller time intervals.

A building energy simulation tool is a computer program consisting of mathematical models of building elements and HVAC&R equipment. To run a building energy simulation, the user must define the building elements, equipment variables, energy cost, etc. The simulation engine then solves mathematical models of the building elements, equipment, and so on 8760 times (one for every hour), usually through a sequential process. Common results include annual energy consumption, annual energy cost, hourly profiles of cooling loads, and hourly energy consumption. Chapter 19 of the 2018 *ASHRAE Handbook—Fundamentals* provides detailed information on energy modeling techniques.

Typically, energy modeling tools must meet minimum requirements to be accepted by rating authorities such as USGBC or local building codes. The following is typical of minimum modeling capabilities:

- 8760 h per year
- Hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation, defined separately for each day of the week and holidays
- Thermal mass effects
- Ten or more thermal zones
- Part-load performance curves for mechanical equipment
- Capacity and efficiency correction curves for mechanical heating and cooling equipment
- Air-side economizers with integrated control
- Design load calculations to determine required HVAC equipment capacities and air and water flow rates in accordance with generally accepted engineering standards and practice
- Tested according to ASHRAE *Standard* 140

Energy modeling is typically used in the following ways:

- As a decision support tool for energy systems in new construction and retrofit projects; that is, it allows analyzing several design alternatives and the selection of the optimal solution for a given criterion
- To provide vital information to the engineer about the building behavior and systems performance during design
- To demonstrates compliance with energy standards such as ASHRAE *Standard* 90.1 (energy cost budget method)
- To support USGBC LEED certification in the Energy and Atmosphere (EA) section
- To model existing buildings and systems and analyzing proposed energy conservation measures (ECMs) by performing calibrated simulation
- Demonstrate energy cost savings as part of measurements and verification (M&V) protocol (by using calibrated simulation procedures)

Energy modeling is used intensively in LEED for New Construction (USGBC 2009), Energy & Atmosphere (EA), prerequisite 2 (minimum energy performance), and for EA credit 1 (Optimize Energy Performance). An energy simulation program (with the requirements shown above) along with ASHRAE *Standard* 90.1 is used to perform whole-building energy simulation for demonstrating energy cost savings. The number of credits awarded is in correlation to the energy cost reduction.

Energy Benchmarking and Benchmarking Tools

Energy benchmarking is an important element of energy use evaluation and tracking. It involves comparing building normalized energy consumption to that of other similar buildings. The most common normalization factor is the gross floor area. Energy benchmarking is less accurate then other energy analysis methods, but can provide a good overall picture of relative energy use.

Relative energy use is commonly expressed by the energy utilization index (EUI), which is the energy use per unit area per year. Typically, EUI is defined in terms of MJ/m^2 per year. In some cases, the user is interested in energy cost benchmarking, which is known as the cost utilization index (CUI). CUI units are $\$/m^2$ per year. It is important to differentiate between site EUI (actual energy used on site) and source EUI (energy used at the energy source); about two-thirds of the primary energy that goes into an electric power plant is lost in the process as waste heat.

One of the most important sources of energy benchmarking data is the Commercial Building Energy Consumption Survey (CBECS) by the U.S. Department of Energy's Energy Information Administration (DOE/EIA). Table 2 of Chapter 37 shows an example of EUI calculated based on DOE/EIA 2003 CBECS; the mean site EUI for mixed-use office space is 89 $MJ/(m^2 \cdot yr)$. Other EUIs for commercial facilities can be found in the same table.

Common energy benchmarking tools include the following:

- U.S. EPA ENERGY STAR Portfolio Manager (http://www.energystar.gov/benchmark)
- Lawrence Berkeley National Laboratory (LBNL) ARCH (http://poet.lbl.gov/arch/)
- CAL-ARCH for the state of California (http://poet.lbl.gov/cal-arch/)

Comprehensive information on energy benchmarking and available benchmarking tools can be found in Glazer (2006) and Chapter 37.

Combined Heat and Power in Commercial Facilities

Combined heat and power (CHP) plants and building cooling heating and power (BCHP) can be considered for large facilities such as large office buildings and campuses and airports when economically justifiable. Chapter 7 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* and other sources such as Meckler and Hyman (2010), Orlando (1996), and Petchers (2002) provide information on CHP systems. Additional Internet-based sources for CHP include the following:

- U.S. EPA Combined Heat and Power (CHP) Partnership at http://www.epa.gov/chp/; procedures for feasibility studies and evaluations for CHP integration are available at http://www.epa.gov/chp/project-development/index.html
- U.S. Department of Energy, Energy Efficiency and Renewable Energy at http://www.energy.gov/eere/amo/chp-deployment
- A database of CHP installations can be found at http://www.eea-inc.com/chpdata/index.html

Maor and Reddy (2008) show a procedure to optimize the size of the prime mover and thermally operated chiller for large office buildings by combining a building energy simulation program and CHP optimization tools.

CHP systems can be applied in large district cooling and heating facilities and infrastructure to use waste heat efficiently. The type of the prime mover is heavily dependent on the electrical and thermal loads, ability to use waste heat efficiently, and utility rates. Table 1 in Chapter 7 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on the applicability of CHP.

Renewable Energy

Renewable energy (RE) technologies, including solar, wind, and biomass, can be considered when applicable and economically justifiable. Renewable energy use can add LEED credits (USGBC 2009) under Energy and Atmosphere (credit 2), depending on the percentage of renewable energy used.

Given the increased number and popularity of solar systems, only these systems will be discussed in this chapter. Geothermal energy is also considered to be renewable energy; these systems are discussed earlier in this chapter, and in more detail in Chapter 35.

Solar/Photovoltaic. Photovoltaic (PV) technology is the direct conversion of sunlight to electricity using semiconductor devices called solar cells. Photovoltaic are almost maintenance-free and seem to have a long lifespan. Given the longevity, no pollution, simplicity, and minimal resources, this technology is highly sustainable, and the proper financing mechanisms can make this system economically justifiable.

Airport facilities can be considered good candidates for PV technology for the following reasons:

- Large, low-rise buildings with available roof for PV collectors
- Little or no shading
- Large open area (open areas, parking lots, etc.)
- Hours and seasons of operation

The most common technology in use today is single-crystal PV, which uses wafers of silicon wired together and attached to a module substrate. Thin-film PV, such as amorphous silicon technology, uses silicon and other chemicals deposited directly on a substrate such as glass or flexible stainless steel. Thin films promise lower cost per unit area, but also have lower efficiency and produce less electricity per unit area compared to single-crystal PVs. Typical values for dc electrical power generation are around 0.56 W/m^2 for thin film and up to 1.4 W/m^2 for single-crystal PV.

PV panels produce direct current, not the alternating current used to power most building equipment. Direct current is easily stored in batteries; an inverter is required to transform the direct current to alternating current. The costs of an inverter and of reliable batteries to store electricity increase the overall cost of a system, which is usually \$5 to \$7/W (Krieth and Goswami 2007).

Another option is concentrated PV (CPV). CPV uses high-concentration lenses or mirrors to focus sunlight onto miniature solar cells. CPV systems must track the sun to keep the light focused on the PV cells. The main advantage of this system is higher efficiency than other technologies. Reliability, however, is an important technical challenge for this emerging technology: the systems generally require highly sophisticated tracking devices.

Being able to transfer excess electricity generated by a photovoltaic system back into the utility grid can be advantageous. Most utilities are required to buy excess site-generated electricity back from the customer. In many states, public utility commissions or state legislatures have mandated **netmetering**, which means that utilities pay and charge equal rates regardless of which way the electricity flows. A good source of rebates and incentives in the United States for solar systems and other renewable technologies is the Database of State Incentives for Renewable and Efficiency (DSIRE), available at http://www.dsireusa.org/ (North Carolina State University 2011). DSIRE is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency, as well as state requirements for licensed solar contractors.

PV systems should be integrated during the early stages of the design. In existing facilities, a licensed contractor can be employed for a turnkey project, which includes sizing, analysis, economic analysis, design documents, specifications, permits, and documentation for incentives.

Available tools for analysis during design and installation of PV systems include the following:

- PVsyst, a PC software package for the study, sizing, simulation and data analysis of complete PV systems (University of Geneva 2010) at http://www.pvsyst.com
- Hybrid Optimization Modeling Software (HOMER 2010), a program for analyzing and optimizing renewable energy technologies (http://www.homerenergy.com/)
- RETScreen (Natural Resources Canada 2010), a free decision support tool (which supports 35 languages) developed to help evaluate energy production and savings, costs, emission reductions, financial viability, and risk for various types of renewable energy technologies, at http://www.retscreen.net/ang/home.php
- eQUEST (Quick Energy Simulation Tool), a full-scale building energy simulation program capable of performing a complete building energy evaluation, at http://www.doe2.com/

Financing PV projects in the public sector can be more complex because of tax exemptions and efficient allocation of public funds and leverage incentives. The primary mechanism for financing public-sector PV projects is a third-party ownership model, which allows the public sector to take advantage of all the federal tax and other incentives without large up-front outlay of capital. The public sector does not own the solar PV, but only hosts it on its property. The cost of electrical power generated is then secured at a fixed rate, which is lower than the retail price for 15 to 25 years. Cory et al. (2008) discuss solar photovoltaic financing for the public sector in detail.

Solar/Thermal. Some commercial facilities can consider active thermal solar heating systems. Solar hot-water systems usually can reduce the energy required for service hot water. Solar heating design and installation information can be found in ASHRAE (1988, 1991). Chapter 37 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* and Krieth and Goswami (2007) are good sources of information for design and installation of active solar systems, as are Web-based sources such as U.S. Department of Energy's Energy Efficiency and Renewable Energy page at http://www.energy.gov/eere/renewables/solar.

Value Engineering and Life-Cycle Cost Analysis

Use of value engineering (VE) and life-cycle cost analysis (LCCA) studies is growing in all types of construction and as part of the integrated design process (IDP). VE and LCCA are logical, structured, systematic processes used as decision support tools to achieve overall cost reduction, but they are two distinct tools (Anderson et al. 2004).

Value engineering refers to a process where the project team examines the proposed design components in relation to the project objectives and requirements. The intent is to provide essential functions while exploring cost savings opportunities through modification or elimination of nonessential design elements. Examples are alternative systems, and substitute equipment. VE typically includes seven steps, as shown in Figure 11 of Chapter 8.

Life-cycle cost analysis is used as part of VE to evaluate design alternatives (e.g., alternative systems, equipment substitutions) that meet the facility design criteria with reduced cost or increased value over the life of the facility or system.

The combination of VE and LCCA is suitable for public facilities, which are often government funded and intended for longer lifespans than commercial facilities. Unfortunately, these tools often are not included in the early stages of the design, which results in a last-minute effort to reduce cost and stay within the budget, compromising issues such as energy efficiency and overall value of the facility. To avoid this, VE and LCCA should be deployed in the early stages of the project.

LCCA is recommended as part of any commercial building construction for economic evaluation. Chapters 38 and 60 discuss LCCA in detail. Other methodologies such as simple payback should be avoided because of inaccuracies and the need to take into account the time value of money. Life-cycle cost is more accurate because it captures all the major initial costs associated with each item, the costs occurring during the life of the system, and the value of money for the entire life of the system.

5. COMMISSIONING AND RETROCOMMISSIONING

Commissioning (Cx) is a quality assurance process for buildings from predesign through design, construction, and operations. It involves achieving, verifying, and documenting the performance of each system to meet the building operational needs. Given the growing demand for enhanced indoor air quality, thermal comfort, noise, etc., in commercial facilities and the application of equipment and systems such as DOAS, EMS, and occupancy sensors, it is important to follow the commissioning process as described in Chapter 44 and ASHRAE *Guideline* 0-2005. The technical requirements for the commissioning process are described in detail in ASHRAE *Guideline* 1.1-2007. Another source is ACG (2005). Proper commissioning ensures fully functional systems that can be operated and maintained properly throughout the life of the building. Although commissioning activities should be implemented by qualified commissioning professional [commissioning authority (CA)], it is important for other professionals to understand the basic definitions and processes in commissioning, such as the following:

- Owner project requirements (OPR), which is a written document that details the functional requirements of the project and the expectations of how it will be used and operated.
- Commissioning refers to a quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all its systems and assemblies are planned, installed, tested, and maintained to meet the OPR.
- Recommissioning is an application of the commissioning process to a project that has been delivered using the commissioning process.
- Retrocommissioning is applied to an existing facility that was not previously commissioned.
- Ongoing commissioning is a continuation of the commissioning process well into the occupancy and operation phase.

Commissioning: New Construction

Table 7 shows the phases of commissioning a new building, as defined by ASHRAE *Guideline* 1.1.

ACG 2005 refers to the following HVAC commissioning processes for new construction:

- Comprehensive HVAC commissioning starts at the inception of a building project from the predesign phase till postacceptance)
- Construction HVAC commissioning occurs during construction, acceptance, and postacceptance (predesign and design phases are not included in this process)

Commissioning is an important element in LEED for new construction (USGBC 2009). As a prerequisite (Energy and Atmosphere, prerequisite 1), commissioning must verify that the project's energy-related systems are installed and calibrated, and perform according to the OPR, BOD, and the construction document. Additional credits (Energy and Atmosphere, credit 3—Enhanced Commissioning) can be obtained by applying the entire commissioning process (or the comprehensive HVAC commissioning) as described previously.

Commissioning: Existing Buildings

HVAC commissioning in existing buildings covers the following:

- Recommissioning
- Retrocommissioning (RCx)
- HVAC systems modifications

Although the methodology for both is identical, there is a difference between recommissioning and retrocommissioning. Recommissioning is initiated by the building owner and seeks to resolve ongoing problems or to ensure that systems continue to meet the facility's requirements. There are can be changes in the building's occupancy or design strategies, outdated equipment, degraded equipment efficiency, occupant discomfort, and IAQ problems that can initiate the need for recommissioning. Typical recommissioning activities are shown in Table 8.

Commissioning is also an important element in existing buildings. USGBC (2009), *LEED for Existing Buildings & Operation Maintenance* awards up to six credits for commissioning systems in existing buildings in the Energy and Atmosphere (EA) section.

HVAC systems modifications can vary from minor modification to HVAC systems up to complete reconstruction of all or part of building HVAC system. The process for this type of project should follow the process described previously for new construction.

6. SEISMIC AND WIND RESTRAINT CONSIDERATIONS

Seismic bracing of HVAC equipment should be considered. Wind restraint codes may also apply in areas where tornados and hurricanes necessitate additional bracing. This consideration is especially important if there is an agreement with local officials to use the facility as a disaster relief shelter. See Chapter 56 for further information.

Table 7 Key Commissioning Activities for New Building

Phase	Key Commissioning Activities
Predesign	Preparatory phase in which the OPR is developed and defined.
Design	OPR is translated into construction documents, and basis of design (BOD) document is created to clearly convey assumptions and data used to develop the design solution. See informative annex k of ASHRAE *Guideline* 1.1-2007 for detailed structure and an example of a typical bod.
Construction	The commissioning team is involved to ensure that systems and assemblies installed and placed into service meet the OPR.
Occupancy and operation*	The commissioning team is involved to verify ongoing compliance with the OPR.

Source: ASHRAE *Guideline* 1.1-2007.
*Also known as acceptance and post-acceptance in ACG (2005).

Table 8 Key Commissioning Activities for Existing Building

Phase	Key Commissioning Activities
Planning	Define HVAC goals
	Select a commissioning team
	Finalize recommissioning scope
	Documentation and site reviews
	Site survey
	Preparation of recommissioning plan
Implementation	Hire testing and balancing (TAB) agency and automatic temperature control (ATC) contractor
	Document and verify tab and controls results
	Functional performance tests
	Analyze results
	Review operation and maintenance (O&M) practices
	O&M instruction and documentation
	Complete commissioning report

Source: ACG (2005).

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CHAPTER 4

TALL BUILDINGS

TALL buildings have existed for more than 100 years and have been built in cities worldwide. Great heights only became possible after the invention of the elevator safety braking system in 1853; subsequent population and economic growth in cities made these taller buildings very popular. This chapter focuses on the specific HVAC system requirements unique to tall buildings.

ASHRAE Technical Committee (TC) 9.12, Tall Buildings, defines a tall building as one whose height is greater than 91 m. The Council on Tall Buildings and Urban Habitat (CTBUH 2014) defines a tall building as one in which the height strongly influences planning, design, or use; they classify recently constructed tall buildings as **supertall** (buildings taller than 300 m) and **megatall** (buildings taller than 600 m).

Traditionally, model codes in the United States were adopted on a regional basis, but recently the three leading code associations united to form the International Code Council (ICC 2018), which publishes the unified *International Building Code*® (IBC). Another important national code, developed by the National Fire Protection Association (NFPA), is NFPA *Standard* 5000®. These codes address the requirements of tall buildings to some extent, but many local or international locations may have their own modifications or alternatives to these model codes.

The overall cost of a tall building is affected by the floor-to-floor height. A small difference in this height, when multiplied by the number of floors and the area of the perimeter length of the building, results in an increase in the area that must be added to the exterior skin of the building. The final floor-to-floor height of the office occupancy floors of any building is jointly determined by the owner, architect, and structural, HVAC, and electrical engineers.

There are increasing numbers of tall buildings in the world (either planned or built) that will have a much greater height than 91 m. There is also a trend that most of the new tall buildings today are of the mixed-use type: for example, many will have a combination of commercial offices, hotel, apartments, observation deck, club floor, etc., stacked on top of each other. Tall buildings with these heights and mixed uses will significantly affect HVAC system design.

Much of the material in this chapter derives from Ross (2004).

1. STACK EFFECT

Stack effect occurs in tall buildings when the outdoor temperature is lower than the temperature of the spaces inside. A tall building acts like a chimney in cold weather, with natural convection of air entering at the lower floors, flowing through the building, and exiting from the upper floors. It results from the difference in density between the cold, denser air outside the building and the warm, less dense air inside the building. The pressure differential created by stack effect is directly proportional to building height as well as to the difference between the warm inside and cold outdoor temperatures.

When the temperature outside the building is warmer than the temperature inside the building, the stack effect phenomenon is reversed. This means that, in very warm climates, air enters the building at the upper floors, flows through the building, and exits at the lower floors. The cause of **reverse stack effect** is the same in that it is caused by the differences in density between the air in the building and the air outside the building, but in this case the heavier, denser air is inside the building.

Reverse stack effect is not as significant a problem in tall buildings in warm climates because the difference in temperature between inside and outside the building is significantly less than the temperatures difference in very cold climates. Accordingly, this section focuses on the problems caused by stack effect in cold climates. Note that these measures can be very different than those in hot and humid climates.

Theory

For a theoretical discussion of stack effect, see Chapter 16 in the 2017 *ASHRAE Handbook—Fundamentals*. That chapter describes calculation of the theoretical total stack effect for temperature differences between the inside and outside of the building. It also points out that every building has a **neutral pressure level (NPL)**: the point at which interior and exterior pressures are equal at a given temperature differential. The location of the NPL is governed by the actual building, the permeability of its exterior wall, the internal partitions, and the construction and permeability of stairs and shafts, including the elevator shafts and shafts for ducts and pipes. Other factors include the air-conditioning systems: exhaust systems that extend through the entire height of the building tend to raise the NPL, thereby increasing the total pressure differential experienced at the base of the building. This also increases infiltration of outdoor air, which tends to lower the NPL, thus decreasing the total pressure differential experienced at the base of the building. Finally, wind pressure, which typically increases with elevations and is stronger at the upper floors of a building, also can shift the neutral plane, and should be considered as an additional pressure to stack effect when locating the neutral plane.

Figure 1 depicts airflow into and out of a building when the outdoor temperature is cold (stack effect) and hot (reverse stack effect). Not shown is the movement of air up or down in the building as a function of stack effect. Assuming there are no openings in the building, the NPL is the point in the building elevation where air neither enters nor leaves the building. Vertical movement of air in the building occurs at the paths of least resistance, including but not limited to shafts and stairs in the building as well as any other openings at the slab edge or in vertical piping sleeves that are less than totally sealed. Figure 1 also indicates that air movement into and out of the building

The preparation of this chapter is assigned to TC 9.12, Tall Buildings.

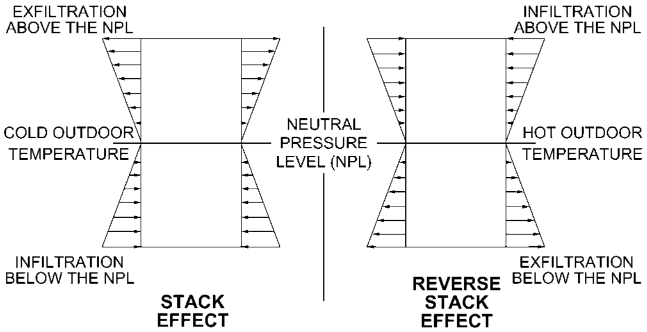


Fig. 1 Airflow from Stack Effect and Reverse Stack Effect
(Ross 2004)

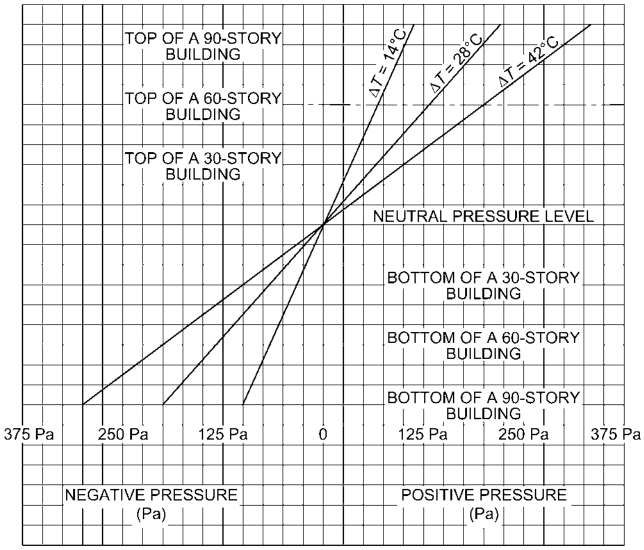
increases as the distance from the NPL increases. Elevator shafts, especially ones that connect the top and bottom of a tall building (e.g., a fire lift), are likely paths of least resistance for airflow. The total theoretical pressure differential can be calculated for a building of a given height and at various differences in temperature between indoor and outdoor air.

The theoretical stack effect pressure gradient for alternative temperature differences and building heights is shown in Figure 2. The diagram shows the potential maximum differentials that can occur (which are significant), but these plotted values are based on an idealized building with no internal subdivisions in the form of slabs and partitions. The plot, therefore, includes no provisions for resistance to airflow in the building. Further, the outer wall's permeability influences the values on the diagram and, as noted previously, the wind effect and operation of the building air-handling systems and fans also affect this theoretical value. Thus, the diagram should be considered an illustration of the possible magnitude of stack effect, not as an actual set of values for any building. The actual stack effect and location of the NPL in any building are difficult (if not in a practical sense impossible) to determine. A real building, especially a tall building, may have multiple neutral planes because of the effects of elevator and stair transfers. Each shaft section (e.g., low-rise elevator shaft) imparts its own stack effect and can create variations in the building pressure profile at the top and bottom of the shaft. Nevertheless, stack effect can be troublesome, and its possible effects must be recognized in the design documentation for a project.

Practical Considerations

Stack effect in tall buildings often presents major problems:

- **Elevator doors** may fail to close properly because of the pressure differential across the doors, which causes the door to bind in its guideway enough that the closing mechanism does not generate sufficient force to overcome it.
- **Elevator piston effect** may be exacerbated by stack effect because of uncontrolled airflow through elevator shafts, particularly in tall buildings with high-speed elevators and minimal shaft clearances around elevator cabs because of building core space restrictions.
- **Manual doors** may be difficult to open and close because of strong pressure created by stack effect.
- **Smoke and odor propagation** through the air path of stack effect can also occur.
- **Noise** from excessive airflow through shafts and doors may exist as whistling and whooshing.
- **Heating problems** can occur in lower areas of the building that may be difficult to heat because of a substantial influx of cold air through entrances and across the building's outer wall (caused by higher-than-anticipated wall permeability). Heating problems can be so severe as to freeze water in sprinkler system piping, cooling coils, and other water systems on lower floors. The National Association of Architectural Metal Manufacturers (NAAMM) specifies a maximum leakage per unit of exterior wall area of 0.00003 cm^3/m^2 at a pressure difference of 75 Pa exclusive of leakage through operable windows. In reality, tall buildings in cold climates can exceed this pressure difference through a combination of stack, wind, and HVAC system pressure. Even when leakage similar to the NAAMM criterion is included in project specification, it is not always met in actual construction, thereby causing potential operational problems.
- **Fan operational issues** may occur if systems fans are not designed and controlled to overcome the static pressure developed by stack effect.



NOTES:
1. ΔT equals differences between condition inside and outside building.
2. Floor-to-floor height for alternative buildings is assumed to be 4.0 m.

Fig. 2 Theoretical Stack Effect Pressure Gradient for Various Building Heights at Alternative Temperature Differences
(Ross 2004)

Calculation

Uncontrolled infiltration and ventilation is caused by climate, wind pressure, and stack effect; environmental factors associated with stack effect include wind pressure, stack pressure difference, airflow rate, outdoor and indoor temperature, building height, and building construction.

Wind creates a distribution of static pressure on the building envelope that depends on wind direction and velocity against the building envelope. The basic formula to determine this pressure can be expressed as

$$\Delta P_W = P_o + CC_p \rho V_w^2/2 \qquad (1)$$

where

ΔP_W = wind pressure above outdoor air (OA) pressure, Pa
C = unit conversion factor, 0.0129
C_p = surface (location on building envelope) pressure coefficient, dimensionless
ρ = air density, kg/m^3 (about 1.2)
V_w = wind speed, m/s
o = outdoor

When using this equation, wind pressure is 25 Pa at 6.7 m/s on the windward side.

Air density varies with temperature. In cold weather, low-density air infiltrates the high-rise building and rises in the building's vertical shafts as it warms, creating stack effect pressure. The basic stack effect theory is expressed as

$$\Delta P_s = C_2 \rho_i g (h - h_{neutral})(T_i - T_o)/T_o \qquad (2)$$

where

ΔP_s = stack pressure difference (indoor – outdoor), Pa
$C_2 \rho_i g$ = air density and gravity constant, 0.01444
h = building height, m
$h_{neutral}$ = height of neutral pressure level, m
i = indoor
T = temperature, K

When using Equation (2), the stack pressure is 274 Pa for a 60-story building with –23°C OA temperature.

Once the wind pressure ΔP_W and stack pressure difference ΔP_s are calculated, total pressure ΔP_{total} can be found, based on indoor and outdoor pressure difference, and used to calculate the airflow rate:

$$\Delta P_{total} = (P_o - P_i) + \Delta P_W + \Delta P_s \qquad (3)$$

Calculation Example. For the calculation examples, New York was selected because it has many tall buildings and a significant range between warm summer and cold winter temperatures (stack effect influences buildings differently at different temperatures). The following example investigates performance in both summer and winter conditions.

ASHRAE climate data were used (see Chapter 14 of the 2017 *ASHRAE Handbook—Fundamentals*) and show the winter and summer temperature and humidity levels, which can be used to calculate stack effect.

Table 1 gives the example parameters, and Figures 3 to 7 show various conditions. As shown in Figure 4, the biggest difference between internal and external pressure occurs in winter, when internal pressure increases along the building height; in summer, it decreases along the height. In addition, when the building gets taller, its NPL on the windward side rises: the extreme is for a building height of 800 m, for which the NPL on the windward side is almost on the top of the building.

Table 1 Parameters for New York Example Building

	Summer	Winter
Outdoor temperature, °C	32.8	–10.3
Indoor temperature, °C	24	20
Relative humidity, %	54	15
Height above sea level, m	54	54
Wind speed, km/h	22.7	22.7
Air pressure, kPa	101	101

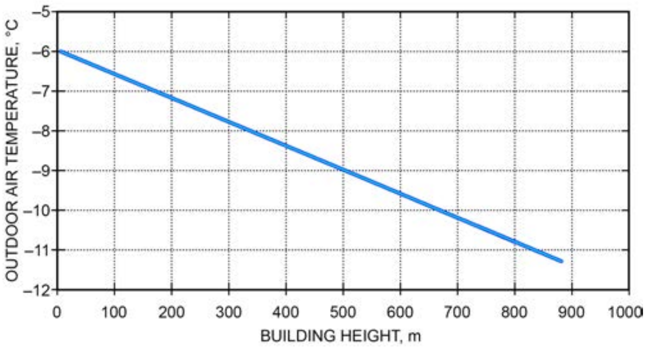


Fig. 3 Reduction in Ambient Temperature Over Height of Building in Cold Ambient Conditions

For the climate in New York, which is cold and dry in winter and warm and humid in summer, **stack effect** is much more intense than in warmer climates. Stack effect during cold outdoor conditions may cause problems, such as elevator doors not closing properly because of the pressure differential across the doors, causing the doors to stick in their guideways if the closing mechanism cannot overcome this friction.

Another difference for New York compared with other cities occurs in the wintertime, when **NPL** is slightly lower, or below the

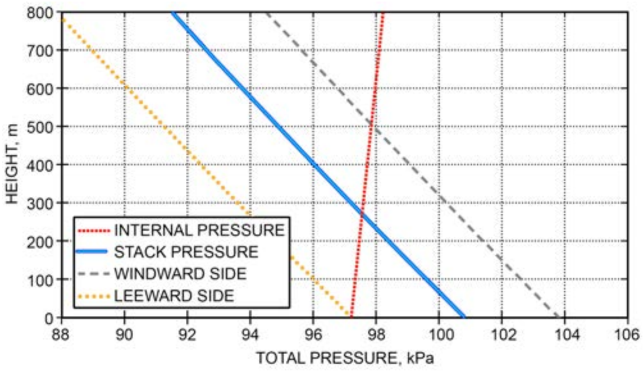


Fig. 4 Windward, Internal, Leeward, and Stack Pressures during Winter

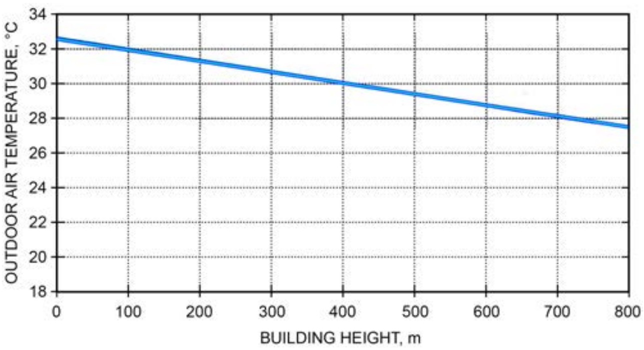


Fig. 5 Reduction in Ambient Temperature over Height of Building in Warm Ambient Conditions

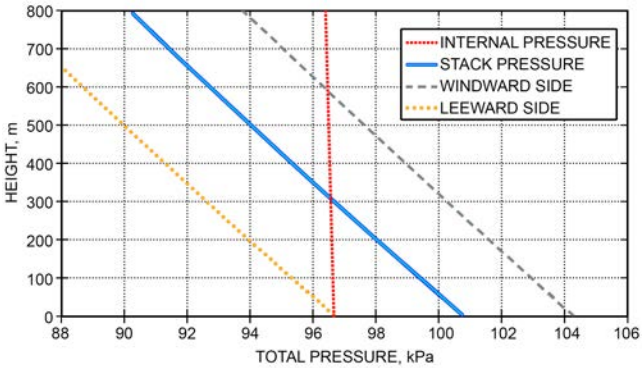


Fig. 6 Windward, Internal, Leeward, and Stack Pressures during Summer

middle of the building. During winter in a 800 m building in New York, the NPL is slightly below 300 m, which means the indoor air pressure is much higher at the upper level of the building than in many other cities. Therefore, for upper levels of the building, air exfiltration is much greater in New York than in other, warmer cities; the airflow rate is higher; and the building function is significantly affected. Stack effect must be addressed during design. Architects and engineers must pay close attention to solving the problems associated with stack effect, which are exacerbated in extremely cold climates.

Minimizing Stack Effect

During design, the architect and HVAC design engineer should take steps to minimize air leakage into or out of (and vertically within) the building. Although it is not possible to completely seal any building, this approach can help mitigate potential problems that could be caused by stack effect.

A tight building envelope and continuous curtainwall system, as well as isolation of vertical shafts from exterior environment through a minimum of two air barriers, are fundamental to protecting a building against uncontrolled air movement into and out of the building. A tight specification, testing, and careful monitoring during construction are required. Although most curtain walls are traditionally tested in the factory, increasingly more field tests (either spot tests or whole-building pressure tests) are specified in some buildings. A whole-building pressure test is difficult in tall buildings, and currently there is a limit on how many floors can be pressurized. Sectionalizing a tall building is required to perform a localized test.

Outdoor air infiltration points include building entry doors, doors that open to truck docks, outdoor air intake or exhaust louvers, construction overhangs with light fixtures, or other recessed items, located immediately above the ground level and are not properly sealed against leakage or provided with heat, and any small fissures in the exterior wall itself. Internally, the building allows air passage through fire stairs, elevator shafts, mechanical shafts for ducts and piping, and any other vertical penetrations for piping or conduit or at the edge of the floor slab at the exterior wall. All these are candidates for careful review to ensure, as much as possible, that the exterior wall is tight, all shafts are closed, and all penetrations sealed. Vestibules or airlocks can be provided for loading docks, with good door seals on the doors to and from the loading dock.

Entrances for tall buildings in cold and hot climates should use revolving doors. Doors of this type are balanced, with equal pressure in opposite directions on the panels on either side of the central pivot, making operation relatively simple and requiring no special effort to turn. Their gaskets also provide closure at all

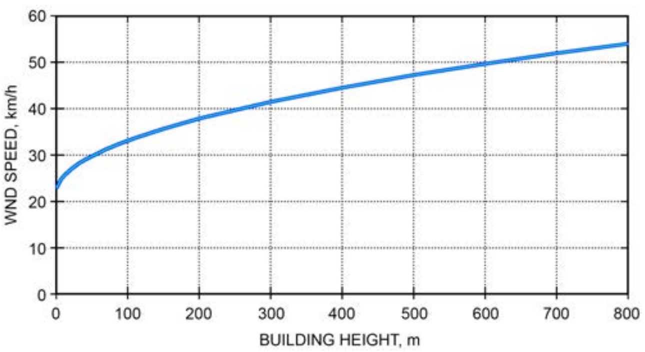


Fig. 7 External Wind Speed as Function of Building Height at Standard Atmospheric Conditions

times. Give special consideration to hotel entries where people carry large luggage through: larger revolving doors are required to avoid people bypassing the revolving doors altogether.

Design and layout of sky lobbies in super- and megatall buildings should be carefully considered to isolate building elevator shafts and exit stairs from the exterior environment. A vestibule may be added at the elevators to provide a second air barrier in addition to the building envelope.

Two-door vestibules are acceptable for the loading dock, assuming the doors are properly spaced to allow them to be operated independently and with one door to the vestibule always closed, and sufficient heat is provided in the space between the doors. If properly spaced, simultaneous opening of both doors on either side of the vestibule can be controlled. However, two-door vestibules in cold climates are inadequate for personnel entry because, with large numbers of people entering the building at various times, both doors will be open simultaneously and significant quantities of unconditioned outdoor air can enter the building. In cold climates, revolving doors are strongly recommended at all points of personnel entry.

To control airflow into the elevator shaft, consider adding doors at the entry to the elevator banks. This creates an elevator vestibule on each floor that minimizes flow through open elevator doors.

Elevator shafts are also a problem because an air opening may be required at the top of the shaft. In many tall buildings, however, the elevator hoistways are not vented for smoke, using sprinkler heads instead. Alternatively, some jurisdictions accept the installation of a motorized damper on the hoistway vent; the damper is initiated by a smoke detector and opens immediately when smoke is sensed in the hoistway. All shafts, however, can be sealed in their vertical faces to minimize inflow that would travel vertically in the shaft to the openings at its top.

Elevator cars can act as pistons to increase the pressure in elevator hoistways ahead of the moving cab. Careful sequencing of elevator cabs, especially when multiple cabs are located in a single shaft, must be considered to provide proper relief and sequencing of door openings.

It can be helpful to interrupt stairs intermittently with well-sealed doors to minimize vertical airflow through buildings. This is particularly useful for fire stairs that extend through the entire height of the building. Entrances to fire stairs should be provided with good door and sill gaskets. (See the section on Door-Opening Forces under Pressurization System Design in Chapter 54 for guidance on ensuring doors in fire stairs can be opened during an emergency.)

Building air supply and pressurization systems should be configured in a maximum of 20- to 40-floor increments to facilitate effective building pressurization corresponding to building stack effect and wind pressure profiles.

The last key item is to ensure a tight exterior wall, which requires specification, proper testing, and hiring a qualified contractor to erect the wall.

The preceding precautions involve the architect and allied trades. The HVAC designer primarily must ensure that mechanical air-conditioning and ventilation systems supply more outdoor air than they exhaust, to pressurize the building above atmospheric pressure. This is true of all systems where a full air balance should be used for the entire building, with a minimum of 5% more outdoor air than the combination of spill and exhaust air provided at all operating conditions, to ensure positive pressurization. In addition, it is good design, and often required by code for smoke control, to have a separate system for the entrance lobby. Although not always required, this system can be designed to operate in extreme winter outdoor air conditions with 100% outdoor air. This air is used to pressurize the building lobby, which is a point of extreme vulnerability in minimizing stack effect. Lastly, if two-door vestibules must be provided, consider pressurizing the vestibule with conditioned outdoor air.

Wind and Stack Effect Pressure Analysis

The world trend toward super- and megatall buildings suggests that both wind and stack effect will greatly affect designs of future tall building and HVAC systems. It is advisable to carry out both wind and stack effect analyses by computational fluid dynamic (CFD) or wind tunnel analysis during concept and schematic design phases of the project, such that advance precautionary measures could be implemented in the early design stage.

Safety Factors

System designers typically apply safety factors at various points in the design process to avoid undersizing equipment. Judicious use of safety factors is good engineering practice. However, safety factors are too often misapplied as a substitute for engineering design, and this practice typically results in grossly oversized equipment. Therefore, care is necessary in applying safety factors.

2. SYSTEMS

Systems used in tall buildings have evolved to address owners' goals, occupants' needs, energy costs, and environmental concerns (including indoor air quality).

Chapter 37 discusses mechanical maintenance and life-cycle costing, which may be useful in the evaluation process with regard to alternative systems. Chapter 1 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* provides guidelines for a quantitative evaluation of alternative systems that should be considered in the system selection process. Chapter 19 of the 2017 *ASHRAE Handbook—Fundamentals* provides means for estimating annual energy costs. Ross (2004) provides a more detailed discussion of systems to be considered.

3. SYSTEM SELECTION CONSIDERATIONS

In a fully developed building (including the core and shell as well as space developed for occupancy), the cost of mechanical and electrical trades (i.e., HVAC, electrical, plumbing, and fire protection) is typically 30 to 35%, and for a high-rise commercial building is usually over 25%, of the overall cost (exclusive of land). In addition, the mechanical and electrical equipment and associated shafts can consume 7 to 10% of the gross building area. The architectural design of the building's exterior and the building core is fundamentally affected by the system chosen. Consequently, HVAC system selection for any tall building should involve the entire building design team (i.e., owner, architect, engineers, and contractors), because the entire team is affected by this decision.

The points of concern and analysis methods do not differ in any way from the process that would be followed for a low-rise building. Possible alternative systems also are very similar, but the choices for high-rise buildings are typically more limited.

Air-Conditioning System Alternatives

Several alternative systems are used in tall buildings. Although the precise system configurations are subject to the experience and imagination of the design HVAC engineer, the most common ones are variations of generic all-air and air/water systems.

Unitary, refrigerant-based systems, such as through-the-wall units, are used in conjunction with all-air systems providing conditioned ventilation air from the interior zone, but this combined solution has been limited to retrofits of older buildings that were not previously air conditioned and smaller low-rise projects. They are seldom used in first-class tall commercial buildings.

Another option is panel-cooling-type systems, including chilled-ceiling and chilled-beam systems. Though not common in the United States, these systems are used in Europe as a retrofit alternative in existing buildings that were not previously air conditioned, because these systems can be installed with minimal effect on existing floor-to-ceiling dimension.

All-Air Variable-Air-Volume Systems. All-air variable-air-volume (VAV) systems in various configurations are one of the most common solutions in tall buildings. Conditioned air for VAV systems can be provided from a central fan room or from local floor-by-floor air conditioning units. These alternative means of delivering conditioned air are discussed in the section on Central Mechanical Equipment Room Versus Floor-by-Floor Fan Rooms. This section is primarily concerned with system functioning, configurations in use, and possible variations in system design.

VAV systems control space temperature by directly varying the quantity of cold supply air in response to the cooling load requirements. VAV terminals or boxes are available in many configurations; pressure-independent terminal units are recommended. Interior spaces that have a year-round cooling load regardless of outdoor air temperature can use any of the alternative types of VAV boxes:

- A **single-duct VAV terminal** reduces supply air volume directly with a reduction of the cooling load. This is a very common terminal in commercial projects, and has the smallest height of any terminal used in office buildings. Usually a stop is used to maintain minimum airflow, for proper ventilation.
- A **series-flow fan-powered VAV terminal** maintains constant airflow into a space by mixing the required amount of cold supply air with return air from the space. The VAV terminal contains a small fan to deliver constant airflow to the space. The fan operates any time the building is occupied. The primary advantage of the fan-powered box is that airflow in the space it supplies is constant at all conditions of load. This is of particular import if low-temperature air is used to reduce the distributed air quantity and the energy necessary to distribute the system air. In cold climates and when the perimeter serving terminal unit locations are at ideal distance from the perimeter wall, the series-flow fan-powered terminal continuously recovers internal heat to be used for partial heat of perimeter spaces.
- A **parallel-flow fan-powered VAV terminal** maintains variable airflow into a space and mixes the required amount of cold supply air at minimum flow requirements with return air from the space. The VAV terminal contains a small fan that starts only in heating mode to deliver mixed primary and return airflow to the space. The fan operates only when heating is required to deliver warm return air, mixed with cool primary air when the building is occupied. Unlike the series-flow box, this option delivers increased airflow to the space during heating but can also shut off primary air and operate only the fan to deliver return air during unoccupied periods. A box-mounted heating coil (hot-water or electric) supplements the heat provided by return air when heating requirements increase. The parallel approach does not ensure constant air volume to the space, as can be obtained with the series approach, but it does provide a minimum airflow at significantly lower operating cost.
- An **induction box** reduces supply air volume and induces room air to mix with supply air, thus maintaining a constant supply airflow to the space. These units require higher inlet static pressure to achieve velocities necessary for induction, with a concomitant increase in supply fan energy requirements. Moreover, operational problems have been experienced, especially at reduced primary airflow quantities. Thus, these boxes are now seldom used in commercial projects.

The exterior zone can use any VAV box type, but in geographical locations requiring heat, the system must be designed with an auxiliary means of providing the necessary heating. This can be done by installing hot-water baseboard, controlled either directly by thermostat or by resetting the hot-water temperature inversely with the outdoor air temperature. Other alternatives are thermostatically controlled electric baseboard on the exterior wall, or either electric or hot-water heating coils in the perimeter VAV boxes.

Low-Temperature-Air VAV Systems. All of the preceding variations can be designed using conventional temperature differentials (9 and 11 K) between the supply air and room temperature. Buildings have been successfully designed, installed, and operated for decades with low-temperature supply air between 8.9 and 10°C. This increases the temperature supply differential to approximately 16 K, thus dramatically reducing primary air quantities and subsequently reducing air-handling system size and air duct distribution.

This lower-temperature air can be obtained by operating the refrigeration machines with chilled water leaving at 4.4°C or by using ice storage. If the chiller supplies 4.4°C chilled water, operating costs of the refrigeration plant increase and the chiller must operate for a longer time before an economizer cycle can occur. Moreover, use of absorption refrigeration machines may not be possible, because they usually cannot provide chilled water as cold as 4.4°C.

However, the reduced quantity of air distributed also reduces fan power, which more than offsets the additional energy used by the chiller. This lower-temperature air requires series-flow fan-powered VAV terminals or induction-type air supply terminals to mitigate draft and dumping concerns at the diffuser due to supplying low-temperature air directly to the space. The air delivery terminals mix room and cold supply air to deliver warmer air to the space to offset heat gain.

Using low-temperature supply air requires elimination of air leaks and proper installation of the correct thickness of duct insulation to prevent moisture condensation. Note that the decrease in supply duct size when using cold air can make lower floor-to-floor heights more practical.

Underfloor Air Distribution (UFAD) Systems. In underfloor air distribution (UFAD) systems, the space beneath a raised floor is used as a distribution plenum. Most installations use manually adjustable supply diffusers or automatically controlled terminal units beneath the floor to control air delivered to the space above. (In contrast, for more traditional systems, terminal units are installed above the ceiling and supply air is delivered from above.) When properly designed, either underfloor or ceiling-mounted air distribution systems can meet occupants' comfort requirements. UFAD systems typically have a higher first cost because of the raised floor, but operating costs are usually lower because less fan power is required. However, if a raised floor is a design requirement for electrical distribution and information technology cabling, UFAD may offer savings in overall first and operating costs.

The UFAD system can use central fan rooms or floor-by-floor fan units. Conditioned air is typically provided at 16 to 18°C in the raised-floor plenum (between the structural slab and the raised floor), but in locations requiring dehumidification, the air must first be cooled to approximately 12.8°C to remove moisture and then blended with return air (often using an underfloor-mounted series fan-powered box or similar arrangement) to achieve supply air temperatures of 16 to 18°C. The suspended ceiling acts as a return plenum but can be reduced in depth because of the absence of supply ductwork.

A major concern with UFAD in tall buildings is the perimeter zone, which has widely varying loads between summer and winter conditions, especially in buildings with large glass exterior elements. Thermostatically controlled fan-coils beneath the floor or finned-tube radiation along the perimeter walls can be cost-effective solutions. Additionally, extreme caution is needed in sealing all structural floor penetrations to prevent short-circuiting of supply air.

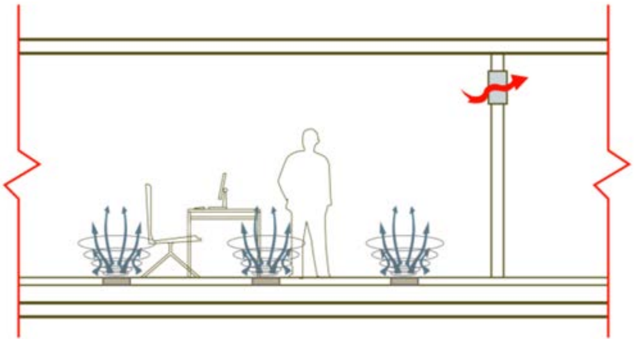


Fig. 8 Typical UFAD System

Underfloor air conditioning for a tall building must be selected early in the design process, because it affects architectural (e.g., floor-to-floor heights, exterior facade treatment, stairs, elevators), structural (e.g., depressed structural slabs), and electrical (e.g., plenum-rated cabling) design considerations. All design disciplines must be involved in this decision process.

The combination of system components and the resultant system configuration for a specific building are limited only by the designer's imagination. The chosen alternative is of interest and concern to the owner, architect, and other engineering consultants, and should be subjected to scrutiny and review by the entire design team before final selection is made.

Underfloor air-conditioning systems are a newer approach, where the space beneath the raised floor is used as a distribution plenum or where terminal units are installed beneath the raised floor (in contrast with more traditional systems, where the terminal units are installed above the ceiling). Either system, with ceiling-mounted terminals or one distributing air through the raised floor, when properly designed, will meet occupants' comfort requirements. The underfloor air-conditioning system typically has higher first cost than comparable overhead distribution systems because of the cost of the raised-floor system. The cost premium can vary as a function of design details for the project, and can be substantially offset if the owner decides to incorporate a raised floor for power wiring and information technology cable distribution. Without this fundamental decision, the increase in the cost of the floor itself and a possible increase in the floor-to-floor height, with the resultant premium that must be paid for the exterior wall and the extended internal shafts, piping, and stairs, may be too great to justify the inclusion of the underfloor distribution system. Figure 8 shows a typical underfloor conditioning/ventilation system.

Multiple variations of underfloor air-conditioning system design are possible. Underfloor air distribution systems use the principle of displacement ventilation. Designs typically are implemented with all-air systems in which air is distributed beneath the floor, with the void between the slab and the raised floor serving as a supply air plenum. The conditioned air is provided at relatively elevated temperatures of approximately 16 to 18°C by blending cold, dehumidified supply air with warm return air. This air then passes at low velocities from the air-conditioned floor through floor outlets and rises vertically to the ceiling through its own buoyancy, removing heat from occupants, office equipment, and lighting as it rises. The ceiling and the space above it function as a return air plenum where distributed air is collected and returns to the air-conditioning supply system, which can be either a central or floor-by-floor system. Because supply ductwork is not needed, the plenum above the ceiling can be reduced in depth compared to that required for an overhead distribution system.

A variation of the underfloor air-conditioning system is using all-air terminals or fan-coil units beneath the floor in the exterior zone.

A thermostatically controlled terminal can be advantageous in altering unit capacity in the exterior zone with its widely varying loads. In addition, using a fan-coil unit, which can modify its capacity output as the load varies and has an inherently greater capacity on a percent basis than an all-air terminal, may provide a more cost-effective solution for tall commercial buildings, particularly those with larger glass elements in the exterior wall. The design using fan-coil units is the same as with all-air terminal designs: air is distributed through floor grilles, with the ceiling acting as a return air plenum.

Many commercial and office projects in Europe include a raised floor for power wiring and information technology cabling, so underfloor distribution systems have been widely accepted throughout the continent. These systems have found more limited application in the United States, probably because raised floors are used infrequently and the *National Electric Code*® (NFPA *Standard* 70) requires that all cabling in an air plenum must be installed in conduit or carry a plenum rating if the raised floor is used for free discharge of supply air. (Where a raised floor is used for cable distribution only, conduit or plenum-rated cabling is not required.) This can increase the cost of cabling significantly and can therefore be a significant consideration in the decision process.

Underfloor distribution systems using variable-air-volume or fan-coil terminals are applied more widely. These systems have a lower space reconfiguration cost as occupancy changes, because all that is required is relocation of a floor diffuser to meet the altered space needs (akin to relocation of an electrical outlet to serve a new occupant layout). This lower cost of interior modifications should be fully considered by the owner and the design team.

Floor supply systems that mix with the total air mass in the occupied zone are not displacement systems. Displacement systems result in temperature gradients in the occupied space, whereas fully mixed systems minimize room temperature gradients.

The displacement system effectively delivers supply air to those parts of the space where heat gain occurs and not the whole occupied volume, so less supply air should be needed.

Fully mixed floor supply systems can handle spaces with high heat gains (>100 W/m^2), and have considerably greater capacity than displacement systems alone (~40 W/m^2). The floor supply system creates zones of discomfort near the outlet, between 1 and 1.5 m radius, where sedentary occupants should not be located. There is a relatively low air volume per outlet compared with high-level diffuser systems, which require the use of more supply outlets.

Because the air supply stream is delivered directly into the occupied zone, supply velocity and temperature are restricted, limiting maximum sensible cooling load to 40 W/m^2 for a 3 m high floor to ceiling height; higher loads can be handled where the floor-to-ceiling height is greater.

Use great caution with floor-to-ceiling heights less than 3 m, because the higher temperatures developed at the ceiling may cause uncomfortable radiant effects. System performance improves with ceiling height.

Consider using exhaust air heat recovery. Recirculation of room air should be minimized, because this air will be hot and vitiated, generally with a higher specific enthalpy than outdoor air.

If air patterns in the space are subject to considerable disruption (e.g., by occupant movement or high infiltration rates), system effectiveness will be reduced.

A displacement ventilation system should not be used for heating because the low-velocity heated air makes effective air distribution very difficult. A separate perimeter heating system should be provided.

Selection of supply outlets should be based on minimizing the zone of discomfort around the supply outlet; this entails using more small outlets rather than fewer large ones. The geometry of the supply outlet is not as critical as that for diffusers and registers used in conventional mixing systems.

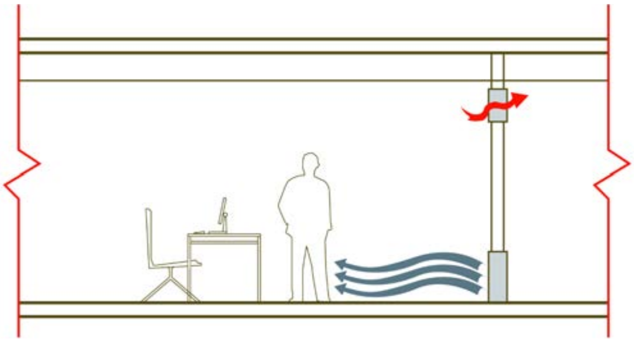


Fig. 9 Displacement Ventilation System Diagram

Match the supply volume flow to the volume flow rate of the plumes set up by internal heat sources at the given boundary height.

The height of the boundary plane depends on supply air volume: it will be higher if excessive air is delivered, and lower if supply air is insufficient.

4. DISPLACEMENT VENTILATION

Displacement ventilation effectiveness is improved compared to conventional mixed systems, which depend on dilution to reduce contaminants. However, system success relies on reasonable ceiling heights and maintaining relatively fragile air movement patterns.

The system works better with a high temperature difference between supply and exhaust air, and is not suitable for applications that require tight temperature and humidity control. In this respect, displacement ventilation functions better where a large floor-to-ceiling height exists and therefore favors applications such as industrial spaces or large auditoriums, atriums, concourses, and some office spaces, where higher ceiling heights mean higher extract temperatures can be tolerated.

Figure 9 shows the principle of a typical displacement ventilation system.

Displacement ventilation has the potential for improving energy efficiency and indoor air quality control for the following reasons:

- There is little mixing between contaminants and bulk air, thereby improving air quality.
- Ventilation is more effective, so fan energy requirements are lower.
- Higher supply temperature means greater use can be made of free cooling of outdoor air. There are, however, some potential pitfalls that may reduce the benefits, such as heating performance; disruption of air patterns in the space by infiltration, occupancy traffic, or other cooling sources (e.g., chilled beams); and dehumidification control.

Displacement ventilation is based on the concept of an ideal airflow pattern. Instead of total mixing achieved by other air distribution systems, the flow is unidirectional, with the minimum spreading of contaminants as possible. This ideal airflow pattern can be achieved by supplying air to the room at low level at a temperature slightly lower than that of the occupied zone, with the removal of hot, vitiated air at high level.

Supply air enters the occupied space at a low velocity and a relatively high temperature compared with conventional systems. This creates a pool of fresh air, which is distributed evenly across the floor. At local heat sources (e.g., occupants, machinery), the air temperature is raised. The natural buoyancy of the heated air gives rise to air currents.

Cool, clean air rises in the plume created by the heat source and replaces the warmed/contaminated air. The air plume generated from the heat source carries with it odors and gaseous and particulate contaminants emitted in the occupied space. These warm contaminated plumes spread out below the ceiling, and an upper contaminated layer is formed. The art of designing a displacement ventilation system is to ensure this hot contaminated region is outside the occupied zone. The supply and exhaust are balanced to produce a boundary layer above which the air is contaminated, and below which is clean, conditioned air in the occupied zone.

Air/Water Systems. Air/water systems historically included induction systems, but modern systems quite often use fan-coil units outside the building, with interior spaces typically supplied by an all-air variable-air-volume (VAV) system. Exterior zones are typically provided with a constant volume of air from either (1) the interior VAV system in sufficient quantities to meet requirements of ASHRAE *Standard* 62.1's multiple-spaces equation, or (2) a separate dedicated outdoor air system providing exterior-zone outdoor air ventilation. Fan-coil units in a tall building that requires winter heat are usually designed with a four-pipe secondary water system to provide coincidental building heating and cooling to different zones.

An advantage of the air/water system is that it reduces the required capacity of the central supply and return air systems and the size of distribution air ducts, compared to those needed with an all-air system (including low-temperature all-air). At the same time, it reduces the air-conditioning supply system's mechanical equipment room space needs. However, air/water systems require space for heat exchangers and pumps to obtain the hot and cold secondary water needed by the fan-coil unit system.

Chilled Beams

Chilled beams are a type of air/water system that have had increasing success in tall buildings. These units are available in both passive and active types, with active units offering higher capacity. Passive chilled-beam units rely on a combination of radiant and convective heat transfer to provide space conditioning from heated or chilled water delivered to the unit. With active units, primary supply air delivered to the unit causes induced room air to circulate through a hot- or chilled-water coil to provide additional conditioning capacity.

Chilled beams allow an overall reduction in the ductwork required to condition the space, because water has a greater heat-carrying capacity than air. Consequently, sheet metal costs and potentially space requirements for supply and return air ductwork can also be reduced. Use caution, however, because chilled-beam units have no condensate drain and should be designed without latent cooling capacity, so the primary supply air must be conditioned to deliver air at a low enough dew point to provide the required dehumidification of the space served.

Radiant Ceilings

Radiant cooling follows the same principles as radiant heating: heat transfer occurs between the space and the panels through a temperature differential. However, unlike in radiant heating, the colder ceiling absorbs thermal energy radiating from people and their surroundings. The major difference between cooled ceilings and air cooling is the heat transport mechanism. Air cooling uses convection only, whereas cooled ceilings use a combination of radiation and convection. The amount of radiative heat transfer can be as high as 55%; convection accounts for the remainder. With cold ceilings, the radiative heat transfer occurs through a net emission of electromagnetic waves from the warm occupants and their surroundings to the cool ceiling. On the other hand, convection first cools the room air because of contact with the cold ceiling, creating convection currents in the space, which transfers the heat from its source to the ceiling, where it is absorbed.

Because air quality must be maintained and radiant panels remove only sensible heat from the space, radiant cooling panels are used in conjunction with a small ventilation system. The panels provide most of the sensible cooling, and the air system provides ventilation and air moisture (latent load) control. To prevent high humidity levels in a room, the supply air must be drier than that of the supplied space, especially when there are additional moisture sources in the room. Consequently, outdoor air must be dehumidified, which is usually done by cooling to a dew point of approximately 15°C. If the environment is dry, the ventilation system is used to humidify the air. Because the ventilation system is used only to maintain the air quality and to regulate the latent load, the airflow required is small relative to conventional cooling systems. Best results are usually attained with a straight displacement ventilation system with no air recirculation. This system typically supplies air through outlets near or at the floor, at temperatures below that of the room air; this approach provides a uniform layer of fresh air at floor level. In turn, people and other heat sources create a passive convective flow of fresh air to the ceilings, where it can be exhausted. This reduced airflow and radiant panels' relatively high surface operating temperature (mean temperature of 16°C) make radiant cooling a more comfortable way of cooling a space than conventional systems.

A cooled ceiling operates in direct proportion to the heat load in the room. Typically, a person sitting at a desk emits 130 W of energy, whereas a computer emits 90 to 530 W to its surroundings. The radiant panel capacity should be determined by the operation conditions (water temperature and flow) and the space temperature. The greater the number of people and/or appliances and exposure to sunlight, the greater the space heat load (and therefore greater increased capacity of the cool ceiling). Generally, cool ceilings can handle between 100 and 225 W/m^2 with up to 50% of the ceiling space used for cooling.

Condensation Control

Condensation on the surface of the panels is not a problem with radiant cooling as long as the supply water temperature is properly controlled. Because condensation of water occurs when the panel temperature reaches the space dew-point temperature, proper water temperature control helps avoid condensation. The space dew-point temperature should be monitored by a sensor linked to a controller, which modulates the inlet water temperature accordingly. Therefore, if there is risk of condensation, the water temperature is raised or water flow is shut off. However, the lower the panel's inlet temperature is, the more work the panels do; the inlet temperature should be at least 1 K above the room's dew-point temperature. Consequently, the cooling capacity of a radiant cooling system is generally limited by the minimum allowable temperature of the inlet water relative to the dew-point temperature of the room air.

Variable-Frequency-Drive (VFD) Fan-Coils

Fan-coil units, either vertical stacked or horizontal, are often used in tall hospitality or residential buildings. Built-in variable-frequency drives provide an energy advantage to the overall building energy consumption, as well as improving temperature control in spaces conditioned by these units. For details, see the section on Fan-Coil Unit Systems in Chapter 20 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*.

These units can be either complete with cabinets (which can be exposed in the space) or built into the general construction (less obtrusive to building aesthetics). Vertical units are even available with vertical pipe risers factory installed, reducing field-installed piping and overall construction costs. Although these internal components are generally designed and tested for elevated pressure capabilities, the actual pressure on these components for a particular building height should be investigated.