CHAPTER 5

IN-ROOM TERMINAL SYSTEMS

VERY early in the design of a new building project or renovation, the HVAC design engineer must analyze and ultimately select appropriate systems, as discussed in Chapter 1. Next, production of primary heating and cooling is selected as decentralized (see Chapter 2) or centralized (see Chapter 3). Finally, distribution of heating and cooling to the end-use space can be done by an all-air system (see Chapter 4), or a variety of all-water or air-water systems and local terminals, as discussed in this chapter.

SYSTEM CHARACTERISTICS

Terminal-unit systems can be designed to provide complete sensible and latent cooling and heating to an end-use space; however, most terminal systems are best used with a central ventilation system providing tempered air to the space. Heat can be provided by hot water, steam, or an electric heating coil. Cooling can be provided by either a chilled-water coil or a direct-expansion (DX) coil. Heat pumps (discussed in Chapter 2) can also be used, either with a piped water loop (water-source) or air cooled. In-room terminals usually condition a single space, but some (e.g., a large fan-coil unit) may serve several spaces. Separate thermostats provide individual zone temperature control.

A terminal unit system **with central ventilation** provides the cooling or heating necessary to equalize only the sensible and latent heat gain or loss caused by the building envelope design and occupancy. Ventilation, or primary, air is provided by a separate ducted system, either to the terminal unit or ducted directly to the space.

Terminal units **without central ventilation** require additional coil capacity to heat or cool the ventilation air required for the end space. This is often difficult because of limited row capacity of coils in terminal units. In addition, care must be taken to minimize the risk of frozen coils in the winter, and to have enough cooling capacity to dehumidify ventilation air in the summer. Ventilation air is ducted to the unit through an opening in the building skin. In most climates, these systems are used in perimeter spaces of buildings with high sensible loads and where close control of humidity is not required. Simultaneous heating and cooling in different parts of the building during intermediate seasons is also possible.

In-room terminal systems are used in almost all classes of buildings. They are especially suitable for smaller projects with little space for a central mechanical room, or projects in which low initial cost and simplified installation are important. These systems are installed in

- Office buildings
- Shopping centers
- Manufacturing plants
- Schools
- Health care facilities
- Hotels and motels
- Apartments
- Nursing homes
- Other multiple-occupancy dwellings

They are also suited to air conditioning existing buildings with limited life or income potential. Although the equipment can be applied as a single unit, this chapter covers applying multiple units to form a complete air-conditioning system for a building.

Advantages

- Individual room temperature control allows each thermostat to be adjusted for a different temperature at relatively low cost.
- Separate heating and cooling sources for ventilation air and secondary heating or cooling give occupants a choice of heating or cooling.
- Less space is required for the air distribution system when the only air required is that for ventilation. Space heating and cooling needs are met by piped hot or chilled water.
- The central air-handling apparatus is smaller than that of an all-air system because less air must be conditioned at that location.
- Dehumidification, filtration, and humidification are performed in a central location remote from conditioned spaces.
- Ventilation air is positively supplied and can accommodate constant recommended outside air quantities.
- Space can be heated without operating the air system, using the secondary-water system. Nighttime fan operation is avoided in an unoccupied building. Emergency power for heating, if required, is much lower than for most all-air systems.

Disadvantages

- For many buildings, in-room terminals are limited to perimeter space; separate systems are required for other areas.
- More controls are needed than for many all-air systems.
- Primary-air supply usually is constant with no provision for shutoff. This is a disadvantage in residential applications, where tenants or hotel room guests may prefer to turn off the air conditioning, or where management may desire to do so to reduce operating expense.
- Low primary chilled-water temperature and/or deep chilled-water coils are needed to control space humidity adequately.
- The system is not appropriate for spaces with high exhaust requirements (e.g., research laboratories) unless supplementary ventilation air is provided.

The preparation of this chapter is assigned to TC 9.1, Large Building Air-Conditioning Systems.

- Central dehumidification eliminates condensation on the secondary-water heat transfer surface under maximum design latent load, but abnormal moisture sources (e.g., open windows, cooking, or people congregating) can cause annoying or damaging condensation. Therefore, a condensate pan should be provided as for other systems.
- Low primary-air temperatures require heavily insulated ducts.

Heating and Cooling Calculations

Basic calculations for airflow, temperatures, relative humidity, loads, and psychrometrics are covered in Chapters 6, 29, and 30 of the 2005 *ASHRAE Handbook—Fundamentals*. The designer should understand the interaction of the terminal units with the central ventilation system (if applicable). Central ventilation systems should be designed to provide air cold enough to satisfy all latent cooling requirements in the end space to maintain dry coils in the terminal units. Some terminal units, such as radiant cooling panels and chilled-beams systems, do not provide latent cooling; building finishes can be damaged by condensation if latent cooling requirements are not addressed.

The HVAC designer should work closely with the architect to optimize building envelope design. Close cooperation of all parties during design can reduce building loads, which allows use of smaller mechanical systems.

In-room systems are used primarily in perimeter spaces of buildings with high sensible loads and where close control of humidity is not required. Variation in air-conditioning load for perimeter building spaces causes significant variations in space cooling and heating requirements, even in rooms that have the same exposure. Accordingly, accurate environmental control in perimeter spaces requires individual control.

Terminal units are often sized for the difference in the internal and external cooling and heating loads. **Internal** loads that should be accounted for include heat gain from lights, occupants, computers and other heat-generating equipment.

External loads vary considerably because of solar heat gain, which varies throughout the day. The magnitude and rate of change of this load depend on building orientation, glass area, capacity to store heat, and cloud cover. Constantly changing shade patterns from adjacent buildings, trees, or exterior columns and nonuniform overhangs can cause significant variations in solar load between adjacent offices on the same solar exposure.

Transmission load can be either a heat loss or a heat gain, depending on outside temperature.

Moderate, uniformly positive pressurization of the building with ventilation air is normally sufficient to offset summer infiltration. In winter, however, infiltration can cause significant heat loss, particularly on lower floors of high-rise buildings. The magnitude of this component varies with wind and stack effect, as well as with the temperature difference across the outside wall.

Space Heating

Some in-room terminal units provide only heating to the end space. Equipment such as cabinet or unit heaters, radiant panels, radiant floors, and finned-tube radiators are designed for heating only. Extreme care must be used with these systems if they are incorporated into a two-pipe changeover piping distribution system, or any other system in which secondary water being piped is not consistently over 100°F. The heating coils in these units are not designed to handle condensation, and there is no drain pipe in the unit. If cold water is provided to these units, dripping condensation from units, valves, or piping may damage building finishes or saturate the insulation, leading to mold growth. Ball valves tied into the automatic temperature control (ATC) system and/or aquastats should be provided to prevent cold water from reaching heating-only terminal units.

Central Ventilation Systems

Generally, the supply air volume from the central apparatus is constant and is called primary or ventilation air to distinguish it from recirculated room air or secondary air. The quantity of primary air supplied to each space is determined by (1) the amount of outside air required for ventilation and (2) the required sensible cooling capacity at maximum room cooling load (if used for sensible cooling). In this approach, during the cooling season, air is dehumidified sufficiently in the central conditioning unit to maintain comfortable humidity conditions and to prevent condensation on the room cooling coil from the normal room latent load. In winter, moisture can be added centrally to limit dryness. As the primary air is dehumidified, it is also cooled to offset part of the room sensible loads. The air may be from outdoors, or may be mixed outside and return air. A heating coil may be required in the central air handler, as well as a preheater in areas with freezing weather.

In the ideal in-room terminal unit design, the secondary cooling coil is always dry; this greatly extends terminal unit life and eliminates odors and the possibility of bacterial growth in the unit in the occupied space. In this case, in-room terminals may be replaced by radiant panels (see Chapter 6) or chilled beams and panels. The primary air normally controls the space humidity. Therefore, the moisture content of supply air must be low enough to offset the room's latent heat gain and to maintain a room dew point low enough to preclude condensation on the secondary cooling surface. Even though some systems operate successfully with little or no condensate, a condensate drain is recommended. In systems that shut down during off hours, start-up load may include considerable dehumidification, producing moisture to be drained away.

Piping Distribution

The chilled or hot water piped to terminal units is called primary or secondary water. The primary air and water are cooled or heated remotely in central equipment rooms.

The water side, in its basic form, consists of a pump and piping to convey water to the heat transfer surface in the unit in each conditioned space. In-room terminals are categorized as two- or four-pipe, and the water may provide heating, cooling, or both, depending on the type of in-room terminal system. They are similar in function and include both cooling and heating capabilities for year-round air conditioning. These piping arrangements are discussed in greater detail in the section on Fan-Coil Units and in Chapter 12.

Other Considerations

In-room terminal systems can provide heating, cooling, and ventilation air to the end space. The amount of ventilation air required depends on the number of occupants in the space and on other factors (see ASHRAE *Standard* 62.1). The rate of airflow per person or per unit area is also usually dictated by state codes, based on activity in the space and contaminant loads. If the amount of ventilation air required is considerable (i.e., 10% or more of a building's entire air volume), the designer needs to provide exhaust or other means to avoid overpressurizing the space.

First, Operating, and Maintenance Costs

As with all systems, the initial cost of an in-room terminal system varies widely, depending on location, local economy, and contractor preference (even for identical systems). For example, a unit ventilator system is less expensive than fan-coil units with a central ventilation system, because it does not require extensive ductwork distribution. The operating cost depends on the system selected, the designer's skill in selecting and correctly sizing components, and efficiency of the duct and piping design. A terminal unit design without a central ventilation system is often one of the less expensive systems to install.

Because in-room terminal equipment is in occupied spaces, maintenance may be more time consuming, depending on the size of the facility. The equipment is less complex, though, and often units are simply replaced, minimizing the time spent in the occupied space.

Energy

The engineer's early involvement in design of any facility can considerably reduce the building's energy consumption. Careful design minimizes system energy costs. In practice, however, a system might be selected based on a low first cost or to perform a particular task. In general, terminal units can save energy if the building automation system (BAS) controls operation of the units and can deenergize them if the space is unoccupied. This adds significant cost to the controls system, but saves on operation. If a central ventilation system is used, energy recovery in the air handler could be another option.

SYSTEM COMPONENTS AND CONFIGURATIONS

Components

Terminal units have many common components, mainly a fan, coil(s), filter, dampers and controls (although some units only have coils and controls).

Automatic Damper. If a terminal unit is providing ventilation air through the envelope of the building, an automatic damper is needed to stop airflow when the room is not occupied. Because in-room terminal units often have a ducted primary or central ventilation air system, a damper on this system allows airflow to be balanced.

Filtration. In-room terminals typically come with a 2 in. throwaway filter. The components that comprise a terminal unit are usually assembled into a cabinet with little room to spare.

Heating and Cooling Coils. Coils in terminal units are usually available in one-, two-, three-, and sometimes four-row coils for cooling and one- or two-row coils for heating.

Fan. Terminal units typically are not complex. Most units have a three-position (low/medium/high) fan that requires manual adjustment. Some larger units serving multiple spaces may have a variable-frequency drive (VSD) on the fan. Fans are also available in direct-drive and belt-drive models.

Piping. Depending on the type of in-room terminal application, terminal units may be furnished and installed with refrigeration, chilled-water, hot-water, and/or condenser water pipe distribution.

Duct Distribution. Terminal units work best without extensive ductwork. With ducts, static pressure on the fan (instead of the coil capacity) may be the determining factor for sizing the terminal units.

Automatic Controls. Most terminal units are controlled with a standard electronic thermostat, either provided by the manufacturer or packaged by the automatic temperature controls (ATC) contractor. The thermostat should be capable of seven-day programming and night setback. Terminal units can be programmed into a BAS, but the cost to do so may be prohibitive, depending on the number of terminal units in the building.

Capacity Control. Terminal unit capacity is usually controlled by coil water flow, fan speed, or both. Water flow can be thermostatically controlled by return air temperature or a wall thermostat and two- or three-way valve. Unit controls may be a self-contained direct digital microprocessor, line voltage or low-voltage electric, or pneumatic. Fan speed control may be automatic or manual; automatic control is usually on/off, with manual speed selection. Units are available with variable-speed motors for modulated speed control. Room thermostats are preferred where automatic fan speed control is used. Return air thermostats do not give a reliable index of room temperature when the fan is off. Residential fan-coil units have manual three-speed fan control, with water temperature (both heating and cooling) scheduled based on outside temperature. On/off speed control is poor because (1) alternating shifts in fan noise level are more obvious than the sound of a constantly running fan, and (2) air circulation patterns in the room are noticeably affected.

Summer room humidity levels tend to be relatively high, particularly if modulating chilled-water control valves are used for room temperature control. Alternatives are two-position control with variable-speed fans (chilled water is either on or off, and airflow is varied to maintain room temperature) and the bypass unit variable chilled-water temperature control (chilled-water flow is constant, and face and bypass dampers are modulated to control room temperature).

Configurations

Terminal units are available in many different configurations; however, not all of the configurations discussed here are available for all types of terminal units. Figure 1 shows several configurations that are particularly applicable for fan-coils.

Low-profile vertical units are available for use under windows with low sills; however, in some cases, the low silhouette is achieved by compromising features such as filter area, motor serviceability, and cabinet style.

Floor-to-ceiling, **chase-enclosed units** are available in which the water and condensate drain risers are part of the factory-furnished unit. Stacking units with integral prefabricated risers directly one above the other can substantially reduce field labor for installation, an important cost factor. These units are used extensively in hotels and other residential buildings. For units serving multiple rooms, the supply and return air paths must be isolated from each other to prevent air and sound interchange between rooms.

Vertical and chase-enclosed models at the perimeter give better results in climates or buildings with high heating requirements. Heating is enhanced by under-window or exterior wall locations. Vertical units can operate as convectors with the fans turned off during night setback, and overheating can become an issue.

Horizontal overhead units may be fitted with ductwork on the discharge to supply several outlets. A single unit may serve several rooms (e.g., in an apartment house where individual room control is not essential and a common air return is feasible). Units must have larger fan motors designed to handle the higher static pressure resistance of the connected ductwork.

Horizontal models conserve floor space and usually cost less, but when located in furred ceilings, they can create problems such as condensate collection and disposal, mixing return air from other rooms, leaky pans damaging ceilings, and difficult access for filter and component removal. In addition, possible condensate leakage may present air quality concerns.

PIPING ARRANGEMENTS

For terminal units requiring chilled and/or hot water, the piping arrangement determines the performance quality, ease of operation, and initial cost of the system. Each piping arrangement is briefly discussed here; for further details, see the sections on Two-Pipe Systems with Central Ventilation, and Four-Pipe Systems.

Four-Pipe Distribution

Four-pipe distribution of secondary water has dedicated supply and return pipes for chilled and hot water. The four-pipe system generally has a high initial cost compared to a two-pipe system, but it has the best system performance. It provides (1) all-season availability of heating and cooling at each unit, (2) no summer/winter changeover requirement, (3) simpler operation, and (4) hot-water heating that uses any heating fuel, heat recovery, or solar heat. In addition, it can be controlled to maintain a dead band between heating and cooling so simultaneous heating and cooling cannot occur.

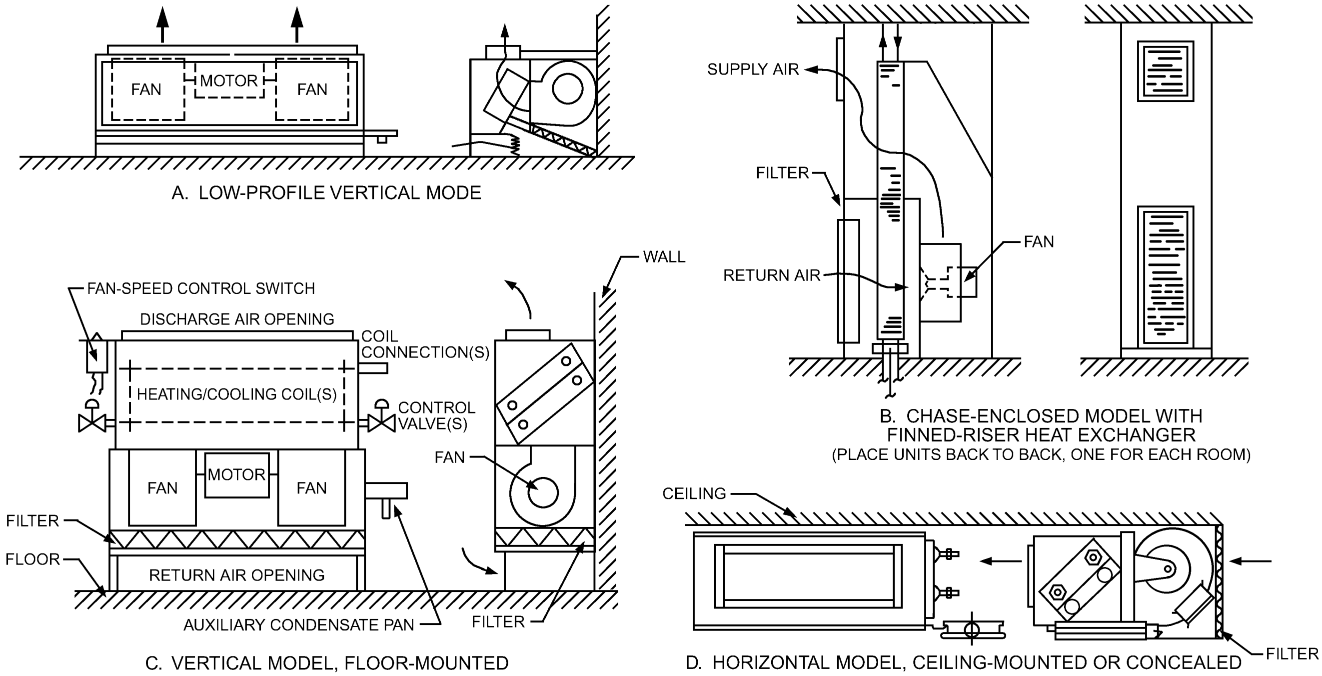


Fig. 1 Typical Fan-Coil Arrangements
(Courtesy RDK Engineers)

Two-Pipe Distribution

Two-Pipe Changeover Without Central Ventilation. In this system, either hot or cold water is supplied through the same piping. The terminal unit has a single coil. The simplest system with the lowest initial cost is the two-pipe changeover with (1) outside air introduced through building apertures, (2) manual three-speed fan control, and (3) hot- and cold-water temperatures scheduled by outside temperatures. This system is generally used in residential buildings or hotels with operable windows and relies on the occupant to control fan speed and open or close windows. The changeover temperature is set at some predetermined set point. If a thermostat is used to control water flow, it must reverse its action depending on whether hot or cold water is available.

The two-pipe system cannot simultaneously heat and cool, which is required for most projects during intermediate seasons when some rooms need cooling and others need heat. This problem can be especially troublesome if a single piping zone supplies the entire building. This deficiency may be partly overcome by dividing the piping into zones based on solar exposure. Then each zone may be operated to heat or cool, independent of the others. However, one room may still require cooling while another room on the same solar exposure requires heating, particularly if the building is partially shaded by an adjacent building or tree.

Another deficiency is the need for frequent changeover from heating to cooling, which complicates operation and increases energy consumption to the extent that it may become impractical. For example, two-pipe changeover system hydraulics must consider the water expansion (and relief) that occurs during cycling from cooling to heating.

Caution must be used with this system when outside air is directly introduced into spaces with widely varying internal loads. Continuous introduction of outside air with reduced load can introduce unconditioned outside air, which can cause very high space humidity levels that may not be able to be handled without reheat capability. The outside air damper in the unit must be motor-operated so it can be closed during unoccupied periods when minimal cooling is required.

For these reasons, the designer should consider the disadvantages of the two-pipe system carefully; many installations of this type waste energy, and have been unsatisfactory in climates where frequent changeover is required and where interior loads require cooling simultaneously as exterior spaces require heat.

Two-Pipe Changeover with Partial Electric Strip Heat. This arrangement provides simultaneous heating and cooling in intermediate seasons by using a small electric strip heater in the terminal unit. The unit can handle heating requirements in mild weather, typically down to 40°F, while continuing to circulate chilled water to handle any cooling requirements. When the outside temperature drops sufficiently to require heating beyond the electric strip heater capacity, the water system must be changed over to hot water.

Two-Pipe Nonchangeover with Full Electric Strip Heat. This system may not be recommended for energy conservation, but it may be practical in areas with a small heating requirement.

Three-Pipe Distribution

Three-pipe distribution uses separate hot- and cold-water supply pipes. A common return pipe carries both hot and cold water back to the central plant. The terminal unit control introduces hot or cold water to the common unit coil based on the need for heating or cooling. This type of distribution is not recommended because of its energy inefficiency from constantly reheating and recooling water, and it does not comply with most recognized energy codes.

FAN-COIL UNIT SYSTEMS

Fan-coil units (1) can provide cooling as well as heating, (2) normally move air by forced convection through the conditioned space, (3) filter circulating air, and (4) may introduce outside ventilation air. These units are available in various configurations to fit under windowsills, above furred ceilings, in vertical pilasters built into walls, etc. Individual room thermostats are usually tied to the piping valve or fan controller in each unit to maintain room temperature. Ventilation air may be provided by a louver in the outside wall and then ducted to the terminal unit, or by a central ventilation system. Fan-coils are also often used in residential applications where ventilation requirements are met by using operable windows.

Basic elements of fan-coil units are a finned-tube heating/cooling coil, filter, and fan section (Figure 2). The fan recirculates air continuously from the space through the coil, which contains either hot or chilled water. The unit may contain an additional electric resistance, steam, or hot-water heating coil. The electric heater is often sized for fall and spring to avoid changeover problems in two-pipe systems; it may also provide reheat for humidity control. A cleanable or replaceable moderate-efficiency filter upstream of the fan prevents clogging of the coil with dirt or lint entrained in recirculated air. It also protects the motor and fan, and reduces the level of airborne contaminants in the conditioned space. The fan and motor assembly is arranged for quick removal for servicing. The fan-coil unit is also equipped with an insulated drain pan.

Most manufacturers furnish units with cooling performance certified as meeting Air-Conditioning and Refrigeration Institute (ARI) standards. The unit prototypes have been tested and labeled by Underwriters Laboratories (UL) or Engineering Testing Laboratories (ETL), as required by some codes. Requirements for testing and standard rating of room fan-coils with air-delivery capacities of 2000 cfm or below are described in ARI *Standard* 440 and ANSI/ASHRAE *Standard* 79.

Fan-coil units for the U.S. market are generally available in nominal sizes of 200, 300, 400, 600, 800, and 1200 cfm, often with multispeed, high-efficiency fan motors. A major advantage of fan-coil unit systems is that the delivery system (piping versus duct systems) requires less building space [a smaller central fan room (or none) and little duct space]. The system has all the benefits of a central water chilling and heating plant, but allows local terminals to be shut off in unused areas. It gives individual room control with little cross-contamination of recirculated air. Extra capacity for quick pulldown response may be provided. Because this system can heat with low-temperature water, it is particularly suitable for use with solar or heat recovery equipment. For existing building retrofit, it is often easier to install piping and wiring for a fan-coil unit system than the large ductwork required for an all-air system.

Fan-coil systems are best applied where individual space temperature control or cross-contamination prevention is needed. Suitable applications are hotels, motels, apartment buildings, and office buildings. Fan-coil systems are used in many hospitals, but they are less desirable because of the low-efficiency filtration and difficulty in maintaining adequate cleanliness in the unit and enclosure. In addition, limits set by *Guidelines for Design and Construction of Hospital and Health Care Facilities* (AIA 2001) do not allow air recirculation in certain types of spaces.

Types and Location

Several types of fan-coils are discussed in the section on System Components and Configurations, and illustrated in Figure 1.

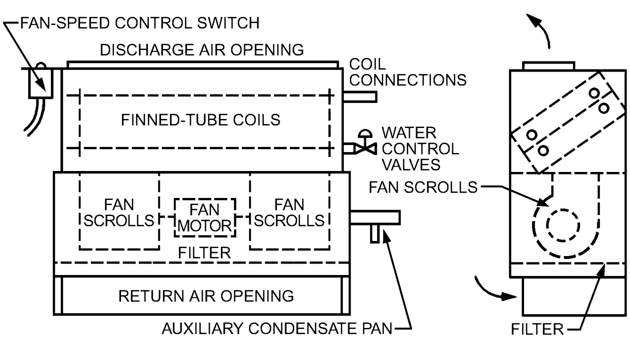


Fig. 2 Typical Fan-Coil Unit

Ventilation Air Requirements

Fan-coil units receive ventilation air from a penetration in the outside wall or from a central air handler. Units that have outside air ducted to them from an aperture in the building envelope are not suitable for commercial buildings because wind pressure allows no control over the amount of outside air admitted. Ventilation rates can be affected by stack effect and wind direction and speed. Also, freeze protection may be required in cold climates. Fan-coils are, however, often used in residential construction because of their simple operation and low first cost, and because residential rooms are often ventilated by opening windows or by outside wall apertures, if not handled by a central system. Operable windows can cause imbalance in a ducted ventilation air system.

When outside air is introduced from a central ventilation system, it may be connected to the inlet plenum of the fan-coil or introduced directly into the space. If introduced directly, ensure that this air is pretreated, dehumidified, and held at a temperature equal to the room temperature so as not to cause occupant discomfort when the space unit is off. One way to prevent air leakage is to provide a spring-loaded motorized damper that closes off ventilation air when the unit's fan is off.

Selection

Some designers size fan-coil units for nominal cooling at medium speed when a three-speed control switch is provided. This method ensures quieter operation in the space and adds a safety factor (capacity can be increased by operating at high speed). Sound power ratings are available from many manufacturers.

If using a horizontal overhead fan coil with ducted supply and return, fan capacity may be the factor that decides the unit's size, not the coil's capacity. Static pressure as little as 0.3 in. of water can significantly affect fan capacity.

Only the internal space heating and cooling loads need to be handled by terminal fan-coil units when outside air is pretreated by a central system to a neutral air temperature of about 70°F. This pretreatment should reduce the size and cost of the terminal units. All loads must be considered in unit selection when outside air is introduced directly through building apertures into the terminal unit.

Wiring

Fan-coil blower fans are driven by small motors, generally shaded pole or capacitor start with inherent overload protection. Operating wattage of even the largest sizes rarely exceeds 300 W at high speed. Running current rarely exceeds 2.5 A. Almost all motors on units in the United States are 120 V, single-phase, 60 Hz current, and they provide multiple (usually three) fan speeds and an off position. Other voltages and power characteristics may be encountered, depending on location, and should be investigated before determining the fan motor characteristics.

In planning the wiring circuit, required codes must be followed. The preferred wiring method generally provides separate electrical circuits for fan-coil units and does not connect them into the lighting circuit.

Separate electrical circuits connected to a central panel allow an energy management system or the building operator to turn off unit fans from a central point during unoccupied hours. Although this panel costs more initially, it can lower operating costs in buildings that do not have 24 h occupancy. In hot, humid climates, care must be taken to avoid excess humidity when units are off, to avoid mildew formation. Using separate electrical circuits allows a single remote thermostat to be mounted in a well-exposed perimeter space to operate unit fans. Another method is to operate the fan-coil continuously on low speed during unoccupied periods.

Condensate

Even when outside air is pretreated, a condensate removal system should be installed for fan-coil units. This precaution ensures that moisture condensed from air from an unexpected source that bypasses the ventilation system (e.g., an open window) is removed. Drain pans are integral for all units. Condensate drain lines should be oversized to avoid clogging with dirt and other materials, and drains should be cleaned periodically. Condensation may occur on the outside of drain piping, which requires that these pipes be insulated. Many building codes have outlawed systems without condensate drain piping because of the potential damage and possibility of mold growth in stagnant water accumulated in the drain pan.

Capacity Control

Fan-coil unit capacity is usually controlled by coil water flow, fan speed, or a combination of these, as discussed in the section on System Components and Configurations.

Maintenance

Fan-coil unit systems require much more maintenance than central all-air systems, and this work must be done in occupied areas. Units operating at low dew points require condensate pans and a drain system that must be cleaned and flushed periodically to prevent overflow and microbial build-up. Drain pans should be trapped to prevent any gaseous back-up. Condensate disposal can be difficult and costly. It is also difficult to clean the coil.

Room fan-coil units are equipped with filters that should be cleaned or replaced when dirty. Filters are small and low-efficiency, and require frequent changing to maintain air volume. Good filter maintenance improves sanitation and provides full airflow, ensuring full-capacity delivery. Cleaning frequency varies with the application. Units in apartments, hotels, and hospitals usually require more frequent filter service because of lint. Fan-coil unit motors may require periodic lubrication. Motor failures are not common, but when they occur, the entire fan can be quickly replaced with minimal interruption in the conditioned space.

UNIT VENTILATOR SYSTEMS

Unit ventilators are similar to fan-coil units, except that unit ventilators are designed to provide up to 100% outside air to the space. They (1) can provide cooling as well as heating, (2) normally move air by forced convection through the conditioned space, (3) filter circulating air, and (4) introduce outside ventilation air as required to meet the needs of the space. These units are available in two main configurations: floor-mounted below a window, or horizontal overhead with ducted supply and return. Most frequently used in classrooms, which need a high percentage of outside air for proper ventilation, unit ventilators are often located under a window along the perimeter wall. Originally, unit ventilators provided only heating, often using steam as the heating source. Now they are available in a two-pipe configuration with changeover, two-pipe with electric heating, four-pipe, or with heating and DX coils for spaces, such as computer rooms, that may require year-round cooling. Limited ductwork is required, allowing for higher and often exposed ceiling systems. The drawback to these units is that they are often used as shelving in the classroom; books and paperwork may be stacked on top of them, impeding airflow to the space. Also, ventilation air intake louvers can become choked by vegetation if they are not properly maintained, which can lead to indoor air quality issues. In addition, because the fans are sized to accommodate 100% ventilation air, they are typically noisier than fan-coils; however, recent research has led to new units that are much quieter.

Basic elements of a unit ventilator are a finned-tube coil, filter, and fan section, and often also a face-and-bypass damper. The fan recirculates air continuously from the space through the coil, which contains either hot or chilled water. The unit may contain an additional electric resistance, steam, or hot-water heating coil. The electric heater is often sized for fall and spring to avoid changeover problems in two-pipe systems, and may also be used to provide reheat for humidity control. A cleanable or replaceable moderate-efficiency filter upstream of the fan prevents clogging of the coil with dirt or lint entrained in recirculated air, protects the motor and fan, and reduces the level of airborne contaminants in the conditioned space. The fan and motor assembly is arranged for quick removal for servicing. The fan-coil unit is also equipped with an insulated drain pan.

Unit ventilators for the U.S. market are generally available in nominal sizes of 750, 1000, 1500, and 2000 cfm, often with multispeed, high-efficiency fan motors. A major advantage of terminal unit systems is that the delivery system (piping versus duct systems) requires less building space [a smaller central fan room (or none) and little duct space]. The system has all the benefits of a central water chilling and heating plant, but allows local terminals to be shut off in unused areas. It gives individual room control with little cross-contamination of recirculated air. Because this system can heat with low-temperature water, it is particularly suitable for use with solar or heat recovery equipment. For existing building retrofit, it is easiest to replace unit ventilators in kind. If a building did not originally use unit ventilators, installing multiple ventilation air intake louvers to accommodate the unit ventilators may be cost-prohibitive. Likewise, attempting to install a different type of system in a building originally fitted with unit ventilators would require bricking up intake louvers and installing exposed ductwork (if there is no ceiling plenum) or creating a ceiling plenum in which to run ductwork. Unit ventilators are best applied where individual space temperature control with large amounts of ventilation air is needed.

Types and Location

Unit ventilators are available in two main configurations. **Floor-mounted units** have different ventilation air ductwork connections, including from the back or ducted collar on the top of the cabinet. **Ceiling-mounted units** can be mounted completely exposed, partially exposed in a soffit, fully recessed, or concealed. Ventilation air connections can be made in the back or top of the unit.

The heating/cooling coils in the unit ventilators differ considerably from fan-coils. Coils in unit ventilators are much deeper, because the unit ventilator needs to be able to heat, cool, and dehumidify up to 100% ventilation air. Coil selection must be based on the temperature of the entering mixture of primary and recirculated air, and air leaving the coil must satisfy the room's sensible and latent cooling and heating requirements.

Ventilation Air Requirements

Unlike fan-coils, unit ventilators are capable of providing the entire volume of ventilation air that is required. Unit ventilators can supply 100% outside air when necessary, because coils in a unit ventilator are deeper than those in fan-coil units.

Selection

Some designers size unit ventilators to provide ventilation air at 50% or less of the total unit airflow. In addition, the coils in the unit ventilator must be selected for the entire heating, cooling, and ventilation loads for the space.

Wiring

Unit ventilator blower fans are driven by small motors, typically 1/2 hp or less. Operating power of even the largest sizes rarely exceeds 400 W at high speed. Almost all motors on units in the United States are single-phase, 60 Hz current, and they provide multiple (usually three) fan speeds and an off position. Other voltages and power characteristics may be encountered, depending on location, and should be investigated before determining the fan motor characteristics.

In planning the wiring circuit, required codes must be followed. The preferred wiring method generally provides separate electrical circuits for unit ventilators and does not connect them into the lighting circuit.

Separate electrical circuits connected to a central panel allow an energy management system or the building operator to turn off unit fans from a central point during unoccupied hours. Although this panel costs more initially, it can lower operating costs in buildings that do not have 24 h occupancy. In hot, humid climates, care must be taken to avoid excess humidity when units are off, to avoid mildew formation. Using separate electrical circuits allows a single remote thermostat to be mounted in a well-exposed perimeter space to operate unit fans. Another method is to operate the unit ventilator continuously on low speed during unoccupied periods.

Condensate

Because unit ventilators can intake up to 100% outside air, condensate piping is required. For floor-mounted units along the perimeter of the building, condensate piping can run from the drain pan to the exterior grade. For a ceiling-mounted unit, the piping could be pitched to the outside wall if there is space available to accommodate the pitch, or a condensate pump could be used. Drain pans are integral for all units. Condensate drain lines should be oversized to avoid clogging with dirt and other materials, and condensate drains should be cleaned periodically. Because condensation may occur on the outside of the drain piping, these pipes must be insulated.

Capacity Control

Unit capacity is usually controlled by coil water flow, fan speed, damper configurations, or a combination of these. In addition, unit ventilators often come equipped with a face-and-bypass damper, which allows for another form of capacity control. For additional information, see the discussion on capacity control in the section on System Components and Configurations.

Maintenance

Maintenance on unit ventilators, such as filter replacement and coil cleaning, must be done in the occupied space. Condensate pans and the drain system must be cleaned and flushed periodically to prevent overflow and microbial build-up. Drain pans should be trapped to prevent any gaseous back-up. Good filter maintenance improves sanitation and provides full airflow, ensuring full-capacity delivery. Cleaning frequency varies with the application. Motors may require periodic lubrication.

CHILLED-BEAM SYSTEMS

Chilled beams are an advancement of chilled ceiling panels. As interior loads have increased with the use of computers and other high-load electrical equipment, so has the need for higher-capacity cooling equipment. Passive chilled beams are the first step. They consist of a chilled-water coil mounted inside a cabinet. Chilled water is piped to the convective coil at between 58 and 60°F. Passive beams use convection currents to cool the space. As air that has been cooled by the beam's chilled-water coil falls into the space, warmer air is displaced, rises into the coil, and is cooled. Passive beams are best used with finned-tube radiation along the space perimeter to provide heat and a separate ventilation system to provide tempered, dehumidified air to the space.

Active chilled beams can provide up to approximately 800 Btu/ft. They operate with induction nozzles that entrain room air and mix it with the primary or ventilation air that is ducted to the beam. Chilled water is piped to the coil at between 55 and 60°F. Primary air should be ducted to the beam at around 55°F and dehumidified. The primary air is then mixed with induced room air at a ratio of 2:1. For example, 50 cfm of primary air at 55°F may be mixed with 100 cfm of recirculated room air, and the active beam would distribute 150 cfm at around 65°F. Active beams can have either a two- or four-pipe distribution system. The two-pipe system may be cooling only or two-pipe changeover. Active beams can be designed to heat and cool the occupied space, but finned-tube radiation is still commonly used to provide heating in a space that is cooled with active beams.

Both active and passive beams are designed to operate dry, without condensate. In some models of active beams, a drain pan may be available if the coil is in a vertical configuration. Horizontal coils in passive beams cannot have drain pans, because the area directly below the coil is needed to allow the air in the convection current to circulate.

Chilled beams can be used in various application; however, they are best used in applications with high sensible loads, such as laboratory spaces with high internal heat gains. See manufacturers' information for beam cooling capacities at various water temperatures and flow rates.

Types and Location

Passive beams are available in sections up to 10 ft long and 18 to 24 in. wide. They can be located above the ceiling with perforated panels below it, mounted into the frame of an acoustical tile ceiling, or mounted in the conditioned space. The perforated panels must have a minimum 50% free area and extend beyond either side of the beam for usually half of the unit's width, so the convection current is not hindered. Also, care must be taken to not locate passive beams too close to window treatments, which can also hinder air movement around the beam.

Active beams are available in sections up to 10 ft long and 12 to 24 in. wide. They can be mounted into the frame of an acoustical tile ceiling or in the conditioned space.

Ventilation Air Requirements

Passive beams require a separate ventilation system to provide tempered and dehumidified air to the space. The ventilation air should be ducted to low-wall diffusers or in an underfloor distribution system so that the ventilation air does not disturb the convection currents in the conditioned space. Ventilation air can be ducted directly into the active beams. If more ventilation air is needed to meet the space requirements, the volume of air can be split by the active beams and high-diffusion diffusers.

Selection

Chilled beams are selected based on the calculated heat gain for the space.

Wiring

Chilled beams only require controls wiring. There is no fan or other electrical equipment to be wired.

Condensate

Chilled beams are designed to operate dry, with few exceptions. In some active beams with vertical coils, a drain pan may be installed. However, as a rule, a separate ventilation system should be sized to handle the latent cooling load in the space, and the relative humidity should be closely monitored.

Capacity Control

Capacity of the chilled beam is controlled by a two-way valve on the chilled-water pipe, which is wired to a room thermostat. There is typically one valve per zone (e.g., office, lecture hall). Beams should be piped directly in a reverse/return piping design. Beams are not typically piped in series.

Maintenance

Maintenance on chilled beams is virtually nonexistent. Most manufacturers require blowing off the coils on a regular basis, but some installations may not need this step.

RADIANT-PANEL HEATING SYSTEMS

Radiant heating panels can use either hot water or electricity. The panels are manufactured in standard 24 by 24 or 24 by 48 in. panels that can be mounted into the frame of an acoustical tile ceiling or directly to an exposed ceiling. Radiant panels are designed for all types of applications. They are very energy efficient, providing a comfortable heat without drying out the room air the way a forced hot-air system may. Occupants in a space heated by radiant heat are comfortable at lower room temperatures, which frequently reduces operational costs. See Chapter 6 for more information on these systems.

Types and Location

Radiant panels are typically mounted on the ceiling in a metal frame. Unlike finned-tube radiation, they do not limit furniture placement. Electric radiant panels are available from 250 to 750 W in standard single-phase voltages.

Ventilation Air Requirements

Radiant panels provide space heating. Ventilation air must be supplied by a central ventilation unit that can provide tempered, dehumidified air to the space.

Selection

Radiant panels are selected based on the calculated heat loss for the space.

Wiring

Electric radiant panels are available in standard single-phase voltages. Panels are often prewired, including the ground wire, with lead wires housed in flexible metal conduit and connector for junction box mounting.

Capacity Control

Panel capacity is usually controlled by coil water flow, or in the case of electric heat, capacity steps. Most radiant panels are controlled with a wall-mounted thermostat located in the space.

Maintenance

Because they have no moving parts, radiant panels require little maintenance.

Other Radiant Panel Options

Radiant panels can also provide space cooling; see the section on Chilled-Beam Systems for design and performance guidelines. Another heating and cooling in-room terminal, the **valance unit** has similar design guidelines.

RADIANT-FLOOR HEAT SYSTEMS

Radiant-floor heat is best applied under a finished floor that is typically cold to the touch. Radiant-floor heat systems in the past used flexible copper pipe heating loops encased in concrete. Unfortunately, the soldered joints could fail or the concrete could corrode the pipes, causing them to leak. However, new technologies include flexible plastic tubing (often referred to as PEX, or cross-linked polyethylene) to replace the old flexible copper tubing. PEX tubing is also available with an oxygen diffusion barrier, because oxygen entrained in the radiant heat tubing can cause corrosion on the ferrous connectors between the tubing and the manifold system. PEX tubing is also available in longer lengths than the flexible copper, which eliminates buried joints. The tubing is run back to a manifold system, which includes valves to balance and shut down the system and a small circulator pump. Multiple zones can be terminated at the same manifold.

Radiant-floor heat is commonly designed for residential applications, where ventilation requirements are often met by operable windows, and cooling is not mandatory. Other applications include large open buildings, such as airplane hangars, where providing heat at the floor is much more cost-effective than heating the entire volume of air in the space. Water in the radiant-floor loop is often around 90°F, depending on the floor finish. This is a lower temperature than forced hot-air systems, and reduces the energy required to heat the building. Buildings that have high ceilings, large windows, or high infiltration rates or that require high air change rates can save additional energy by using radiant-floor heat.

Radiant-floor systems are commonly zoned by room. Each room may require multiple pipe circuits, depending on the room's area and the manifold's location. Maximum tubing lengths are determined based on tubing diameter and desired heat output. If tubing is installed in slab on or below grade, rigid insulation should be incorporated to minimize heat losses to the ground.

See Chapter 6 for more information on these systems.

Types and Location

Radiant-floor heating is located in the flooring or just below it with a heat-reflecting wrap. If the final floor finish is hardwood flooring, the radiant-floor heat can be installed in plywood tracks with a heat reflector, below the finished floor. Care must be taken to ensure that, as the final flooring is nailed down, the flexible tubing is not punctured. If the final floor is a ceramic tile or other surface requiring a poured concrete, the radiant floor can be laid out in the concrete. Radiant-floor heating systems can also be mounted below the floor joists, with a heat reflector below the piping. This method is often used in renovations where removing existing flooring is not feasible.

Ventilation Air Requirements

Ventilation air must be supplied by a central ventilation unit that can provide tempered, dehumidified air to the space.

Selection

Spacing between rows of tubing that make up the radiant floor varies, depending on the heat loss of the space. Usually, the entire heat loss of the space is calculated and the tubing spaced accordingly. Another method is to place tubing closer together near the room's perimeter and increase the spacing in the interior. This method is more time consuming, and the difference is only noticeable in large spaces. Supply water temperature in the tubing is determined based on the flooring materials' resistance to heat flow; the temperature is higher for carpeting and a pad than for ceramic tile. The tubing is also available in different nominal diameters, the most common being 3/8 or 1/2 in.

Wiring

Circulator pumps at the manifolds require power.

Capacity Control

Because radiant floors heat the mass of the floor, these systems are typically slow to respond to environmental changes. The circulator pumps start on a call for heat from a thermostat; however, rapid solar gains to a space with many windows could cause the space to overheat.

Maintenance

The circulator pumps, valves, and manifolds are the only components requiring maintenance. In almost all cases, it is easier to replace a failed component than to repair it. Once the tubing is laid out, it should be pressure-tested for leaks; once covered, it is extremely difficult and/or expensive to access.

INDUCTION-UNIT SYSTEMS

Centrally conditioned primary air is supplied to an induction unit's plenum at medium to high pressure. The acoustically treated plenum attenuates part of the noise generated in the unit and duct. High-velocity induction unit nozzles typically generate significant high-frequency noise. A balancing damper adjusts the primary-air quantity within limits.

Medium- to high-velocity air flows through the induction nozzles and induces secondary air from the room through the secondary coil. Thus, the primary air provides the energy required to circulate the secondary air over the coil in the terminal unit. This secondary air is either heated or cooled at the coil, depending on the season, room requirement, or both. Ordinarily, the room coil does no latent cooling, but a drain pan without a piped drain collects condensed moisture from temporary latent loads such as at start-up. This condensed moisture then re-evaporates when the temporary latent loads are no longer present. Primary and secondary (induced) air is mixed and discharged to the room.

Secondary airflow can cause induction-unit coils to become dirty enough to affect performance. Lint screens used to protect these terminals require frequent in-room maintenance and reduce unit thermal performance.

Induction units are installed in custom enclosures, or in standard cabinets provided by the manufacturer. These enclosures must allow proper flow of secondary air and discharge of mixed air without imposing excessive pressure loss. They must also allow easy servicing. Although induction units are usually installed under a window at a perimeter wall, units designed for overhead installation are also available. During the heating season, the floor-mounted induction unit can function as a convector during off hours, with hot water to the coil and without a primary-air supply. Numerous induction unit configurations are available, including units with low overall height or with larger secondary-coil face areas to suit particular space or load needs.

Induction units may be noisier than fan-coil units, especially in frequencies that interfere with speech. On the other hand, white noise from the induction unit enhances acoustical privacy by masking speech from adjacent spaces.

In-room terminals operate dry, with an anticipated life of 15 to 25 years. The piping and ductwork longevity should equal that of the building. Individual induction units do not contain fans, motors, or compressors. Routine service is generally limited to temperature controls, cleaning lint screens, and infrequently cleaning the induction nozzles.

In existing induction systems, conserving energy by raising the chilled-water temperature on central air-handling cooling coils can damage the terminal cooling coil, causing it to be used constantly as a dehumidifier. Unlike fan-coil units, the induction unit is not designed or constructed to handle condensation. Therefore, it is critical that an induction terminal operates dry.

Induction units are rarely used in new construction. They consume more energy because of the increased power needed to deliver primary air against the pressure drop in the terminal units, and they generate high-frequency noise from the induction nozzles. In addition, the initial cost for a four-pipe induction system is greater than for most all-air systems. However, induction units are still used for direct replacement renovation: because the architecture was originally designed to accommodate the induction unit, other systems may not be easily installed.

SUPPLEMENTAL HEATING UNITS

In-room supplemental heating units come in all sizes. Units can have either electric or hot water heat, and sometimes steam; they can be surface-mounted, semirecessed, or recessed in the walls on the floor or horizontally along the ceiling. Baseboard radiation is usually located at the source of the heat loss, such as under a window or along a perimeter wall, and is usually rated for between 400 and 600 Btu/ft at 170°F. Other supplemental heating units include unit heaters, wall heaters, and cabinet heaters.

All supplemental heating units can be supplied with an integral or separate wall-mounted thermostat. If the heater is located low in the space, an integral thermostat is sufficient most of the time; however, if the unit is mounted horizontally near the ceiling, the thermostat should be wired so that it is located in the space, for accurate space temperature readings. In addition, units may have a summer fan option, which allows the fan to turn on for ventilation. Water flow to space supplemental heaters should be cut off anytime the water temperature to the coil is below 80°F, to avoid condensation and consequent damage or mold growth.

CENTRAL PLANT EQUIPMENT

Central equipment size is based on the block load of the entire building at the time of the building peak load, not on the sum of individual in-room terminal-unit peak loads. Cooling load should include appropriate diversity factors for lighting and occupant loads. Heating load is based on maintaining the unoccupied building at design temperature, plus an additional allowance for pickup capacity if the building temperature is set back at night. For additional information, see Chapter 3.

If water supply temperatures or quantities are to be reset at times other than at peak load, the adjusted settings must be adequate for the most heavily loaded space in the building. Analysis of individual room load variations is required.

If the side of the building exposed to the sun or interior zone loads requires chilled water in cold weather, consider using condenser water with a water-to-water heat exchanger. Varying refrigeration loads require the water chiller to operate satisfactorily under all conditions.

VENTILATION

Central fan equipment is primarily used for an in-room terminal unit system to provide the correct amount of ventilation or makeup air to the various spaces served by terminal units.

Ventilation air is generally the most difficult factor to control and represents a major load component. The designer must select the method that meets all applicable codes, performance requirements, cost constraints, and health requirements.

A central, outside air pretreatment system, which maintains neutral air at about 70°F, best controls ventilation air with the greatest freedom from problems related to the building's stack effect and infiltration. Ventilation air may then be introduced to the room through the terminal unit, or directly into the room as shown in Figure 3. Any type of terminal unit in any location may be used if the outside air ventilation system has separate air outlets.

Ventilation air contributes significantly to the room latent cooling load, so a dehumidifying coil should be installed in the central ventilation system to reduce room humidity during periods of high outside moisture. Centrally supplied air can be supplied at a low

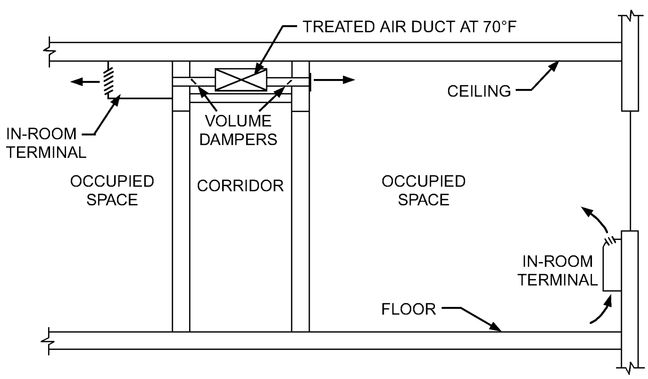


Fig. 3 Ventilation from Separate Duct System

enough dew point to absorb moisture generated in the space, but as a minimum should be supplied at a neutral condition so that the room terminal unit has to remove only the space-generated latent load.

An additional advantage of central ventilation is that, if its supply air dew point is selected to handle the internal latent load, the terminal cooling coil remains dry, extending the unit's life. However, a piped condensate drain is still recommended. This neutral temperature removes the outside air load from the terminal unit, so it can switch from heating to cooling and back without additional internal or external heat loads.

In buildings where terminal units only serve exterior zones and a separate all-air system serves interior zones, exterior zone ventilation air can be provided through the interior zone system. This arrangement can provide desirable room humidity control, as well as temperature control of the ventilation air. In addition, ventilation air held at the neutral condition of 70°F at 50% rh can be introduced into any terminal unit without affecting comfort conditions.

PRIMARY-AIR SYSTEMS

Figure 4 illustrates a primary-air system for in-room terminal systems. The components are described in Chapter 4. Some primary-air systems operate with 100% outside air at all times. Systems using return air should have provision for operating with 100% outside air (economizer cycle) to reduce operating cost during some seasons. In some systems, when the quantity of primary air supplied exceeds the ventilation or exhaust required, excess air is recirculated by a return system common with the interior system. A good-quality filter (55% efficiency or higher) is desirable in the central air treatment apparatus. If it is necessary to maintain a given humidity level in cold weather, a humidifier can usually be installed. Steam humidifiers have been used successfully. Water-spray humidifiers must be operated in conjunction with (1) the preheat coil elevating the temperature of the incoming air or (2) heaters in the spray water circuit. Water-spray humidifiers should be used with caution, however, because of the possible growth of undesirable organisms in untreated water.

The cooling coil is usually selected to provide primary air at a dew point low enough to dehumidify the total system. Supply air must leave the cooling coil at about 50°F or less, and be almost completely saturated.

The supply fan should be selected at a point near maximum efficiency to reduce power consumption, supply air heating, and noise. Sound absorbers may be required at the fan discharge to attenuate fan noise.

Reheat coils are required in a two-pipe system. Reheat is not required for primary-air supply of four-pipe systems. Formerly, many primary-air distribution systems for induction units were designed with 8 to 10 in. of water static pressure. With energy use restrictions, this is no longer economical. Good duct design and

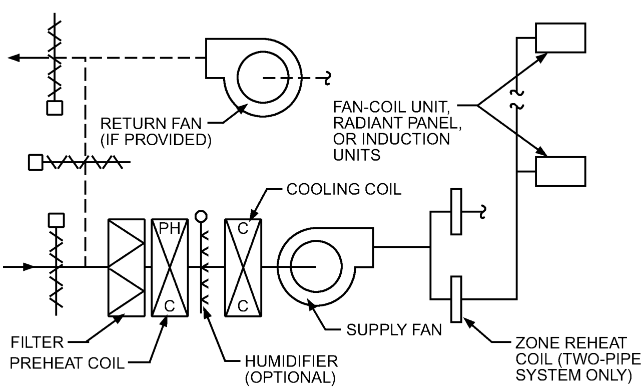


Fig. 4 Primary-Air System

elimination of unnecessary restrictions (e.g., sound traps) can result in primary systems that operate at 4.5 to 6.0 in. of water. Primary-air distribution systems serving fan-coil systems can operate at pressures 1.0 to 1.5 in. of water lower. Careful selection of the primary-air cooling coil and induction units for reasonably low air-pressure drops is necessary to achieve a medium-pressure primary-air system. Distribution for fan-coil systems may be low-velocity or a combination of low- and medium-velocity systems. See Chapter 35 in the 2005 *ASHRAE Handbook—Fundamentals* for a discussion of duct design. Variations in pressure between the first and last terminals should be minimized to limit the pressure drop required across balancing dampers.

Room sound characteristics vary depending on unit selection, air system design, and equipment manufacturer. Units should be selected by considering the unit manufacturer's sound power ratings, desired maximum room noise level, and the room's acoustical characteristics. Limits of sound power level can then be specified to obtain acceptable acoustical performance.

PERFORMANCE UNDER VARYING LOAD

Under peak load conditions, the psychrometrics of induction-unit and fan-coil unit systems are essentially identical for two- and four-pipe systems. Primary air mixes with secondary air conditioned by the room coil in an induction unit before delivery to a room. Mixing also occurs in a fan-coil unit with a direct-connected primary-air supply. If primary air is supplied to the space separately, as in fan-coil systems with independent primary-air supplies, the same effect occurs in the space.

During cooling, the primary-air system provides part of the sensible capacity and all of the dehumidification. The rest of the sensible capacity is accomplished by the cooling effect of secondary water circulating through the unit cooling coils. In winter, primary air is provided at a low temperature, and if humidity control is provided, the air is humidified. All room heating is supplied by the secondary-water system. All factors that contribute to the cooling load of perimeter space in the summer, except transmission, add heat in the winter. The transmission factor becomes negative when the outside temperature falls below room temperature. Its magnitude is directly proportional to the difference between the room and outside temperatures.

For in-room terminal unit systems, it is important to note that in applications where primary air enters at the terminal unit, primary air is provided at summer design temperature during winter. If the economizer cycle is used, heating and cooling energy is not duplicated by reheating primary air that has already been mechanically cooled. For systems where primary air does not enter at the terminal unit, the primary air should be reset to room temperature in winter. A limited amount of cooling can be accomplished by the primary air operating without supplementary cooling from the secondary coil. As long as internal heat gains are not high, this amount of cooling is usually adequate to satisfy east and west exposures during the fall, winter, and spring, because solar heat gain is typically reduced during these seasons. In the northern hemisphere, the north exposure is not a significant factor because solar gain is very low; for south, southeast, and southwest exposures, the peak solar heat gain occurs in winter, coincident with a lower outside temperature (Figure 5). This cooling opportunity may not be available where primary air is supplied directly to the space, because this air could overcool spaces where solar heat gain or internal heat gain is low.

In buildings with large areas of glass, heat transmitted from indoors to the outside, coupled with the normal supply of cool primary air, does not balance internal heat and solar gains until an outside temperature well below freezing is reached. Double-glazed windows with clear or heat-absorbing glass aggravate this condition because this type of glass allows constant inflow of solar radiation during the winter. However, the insulating effect of the

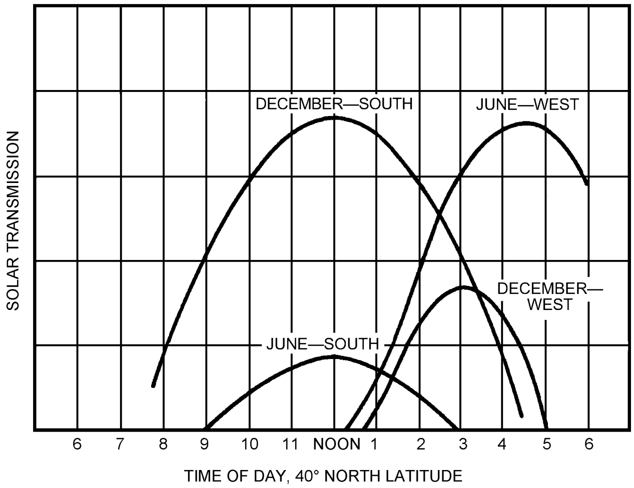


Fig. 5 Solar Radiation Variations with Seasons

double glass reduces reverse transmission; therefore, cooling must be available at lower outside temperatures. In buildings with very high internal heat gains from lighting or equipment, the need for cooling from the room coil, as well as from the primary air, can extend well into winter. In any case, the changeover temperature at which the cooling capacity of the secondary-water system is no longer required for a given space is an important calculation. All these factors should be considered when determining the proper changeover temperature.

CHANGEOVER TEMPERATURE

For all systems using a primary-air system for outside air, there is an outside temperature (a **balance temperature**) at which secondary cooling is no longer required. The system can cool by using outside air at lower temperatures, and heating rather than cooling is needed. For all-air systems operating with up to 100% outside air, mechanical cooling is seldom required at outside temperatures below 55°F. An important characteristic of in-room terminal unit systems, however, is that secondary-water cooling may still be needed, even when the outside temperature is considerably less than 50°F. This cooling may be provided by the mechanical refrigeration unit or by a thermal economizer cycle. Full-flow circulation of primary air through the cooling coil below 50°F often provides all the necessary cooling while preventing coil freeze-up and reducing the preheat requirement. Alternatively, secondary-water-to-condenser-water heat exchangers function well. Some systems circulate condenser water directly through the secondary chilled-water system. This system should be used with caution, recognizing that the vast secondary-water system is being operated as an open recirculating system with the potential hazards that may accompany improper water treatment.

The outside temperature at which the heat gain to every space can be satisfied by the combination of cold primary air and the transmission loss is called the **changeover temperature**. Below this temperature, cooling is not required.

The following empirical equation approximates the changeover temperature at sea level. It should be fine-tuned after system installation (Carrier 1965):

$$t_{co} = t_r - \frac{q_{is} + q_{es} - 1.1 Q_p (t_r - t_p)}{\Delta q_{td}} \qquad (1)$$

where

t_{co} = temperature of changeover point, °F
t_r = room temperature at time of changeover, normally 72°F
t_p = primary-air temperature at unit after system is changed over, normally 56°F
Q_p = primary-air quantity, cfm
q_{is} = internal sensible heat gain, Btu/h
q_{es} = external sensible heat gain, Btu/h
Δq_{td} = heat transmission per degree of temperature difference between room and outside air

In two-pipe changeover systems, the entire system is usually changed from winter to summer operation at the same time, so the room with the lowest changeover point should be identified. In northern latitudes, this room usually has a south, southeast, or southwest exposure because the solar heat gains on these exposures reach their maximum during winter.

If the calculated changeover temperature is below approximately 48°F, an economizer cycle should operate to allow the refrigeration plant to shut down.

Although factors controlling the changeover temperature of induction unit systems are understood by the design engineer, the basic principles may not be readily apparent to system operators. Therefore, it is important that the concept and calculated changeover temperature are clearly explained in operating instructions given before operating the system. Some increase from the calculated changeover temperature is normal in actual operation. Also, a range or band of changeover temperatures, rather than a single value, is necessary to preclude frequent change in seasonal cycles and to grant some flexibility in operation. The difficulties associated with operator understanding and the need to perform changeover several times a day in many areas have severely limited the acceptability of the two-pipe changeover system.

REFRIGERATION LOAD

The design refrigeration load is determined by considering the entire portion or block of the building served by the air-and-water system at the same time. Because the load on the secondary-water system depends on the simultaneous demand of all spaces, the sum of the individual room or zone peaks is not considered.

The peak load time is influenced by the outside wet-bulb temperature, period of building occupancy, and relative amounts of east, south (in the northern hemisphere), and west exposures. Where the solar load's magnitude is about equal for each exposure, the building peak usually occurs in midsummer afternoon when the west solar load and outside wet-bulb temperature are at or near concurrent maximums.

At sea level, the refrigeration load equals the primary-air cooling coil load plus the secondary system heat pickup:

$$q_{re} = q_s + 4.5 Q_p (h_{ea} - h_{la}) - 1.1 Q_p (t_r - t_s) \qquad (2)$$

where

q_{re} = refrigeration load, Btu/h
q_s = block room sensible heat for all spaces at time of peak, Btu/h
h_{ea} = enthalpy of primary air upstream of cooling coil at time of peak, Btu/lb
h_{la} = enthalpy of primary air leaving cooling coil, Btu/lb
Q_p = primary-air quantity, cfm
t_r = average room temperature for all exposures at peak time, °F
t_s = average primary-air temperature at point of delivery to rooms, °F

Because the latent load is absorbed by the primary air, the resultant room relative humidity can be determined by calculating the block room latent load of all spaces at the time of the peak load. Then, recalling that there are 7000 grains in a pound, the rise in moisture content of the primary air at sea level is

$$W = \frac{7000 v_a q_L}{60 h_{fg} Q_p} = 1.48 \frac{q_L}{Q_p} \tag{3}$$

where

W = moisture content rise per lb dry air, grains
v_a = specific volume of air = 13.3 ft^3/lb at sea level
q_L = block room latent load of all spaces at time of peak load, Btu/h
h_{fg} = latent heat of vaporization = 1050 Btu/lb

Then a psychrometric analysis can be performed.

The secondary-water cooling load may be determined by subtracting the primary-air cooling coil load from the total refrigeration load.

TWO-PIPE SYSTEMS WITH CENTRAL VENTILATION

Two-pipe systems for induction and fan-coil systems derive their name from the water-distribution circuit, which consists of one supply and one return pipe. Each unit or conditioned space is supplied with secondary water from this distribution system and with conditioned primary air from a central apparatus. The system design and control of primary-air and secondary-water temperatures must be such that all rooms on the same system (or zone, if applicable) can be satisfied during both heating and cooling seasons. The heating or cooling capacity of any unit at a particular time is the sum of its primary-air output plus its secondary-water output.

The primary-air quantity is fixed, and the primary-air temperature is varied in inverse proportion to the outside temperature to provide the necessary amount of heating during summer and intermediate seasons. During winter, primary air is preheated and supplied at approximately 50°F to provide cooling. All room terminals in a given primary-air preheated zone must be selected to operate satisfactorily with the common primary-air temperature.

The secondary-water coil (cooling-heating) in each space is controlled by a space thermostat and can vary from 0 to 100% of coil capacity, as required to maintain space temperature. The secondary water is cold in summer and intermediate seasons and warm in winter. All rooms on the same secondary-water zone must operate satisfactorily with the same water temperature.

Figure 6 shows the capacity ranges available from a typical two-pipe system. On a hot summer day, loads from about 25 to 100% of the design space cooling capacity can be satisfied. On a 50°F intermediate-season day, the unit can satisfy a heating requirement by closing off the secondary-water coil and using only the output of warm primary air. A lesser heating or net cooling requirement is satisfied by the cold secondary-water coil output,

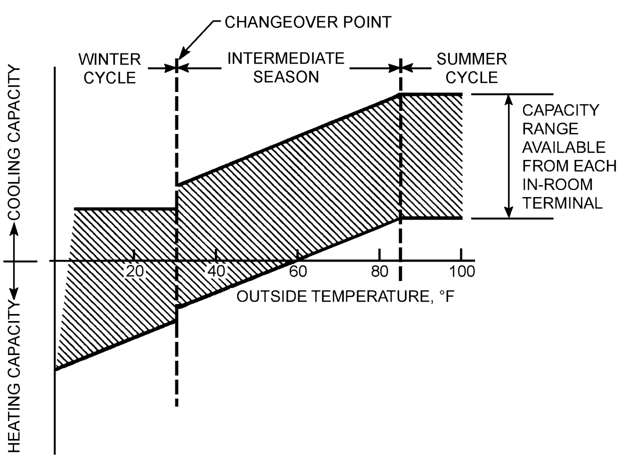


Fig. 6 Capacity Ranges of In-Room Terminal Operating on Two-Pipe System

which offsets the warm primary air to obtain cooling. In winter, the unit can provide a small amount of cooling by closing the secondary coil and using only the cold primary air. Smaller cooling loads and all heating requirements are satisfied by using warm secondary water.

Critical Design Elements

The most critical design elements of a two-pipe system are the calculation of primary-air quantities and the final adjustment of the primary-air temperature reset schedule. All rooms require a minimum amount of heat from the primary-air supply during the intermediate season. Using the ratio of primary air to transmission per degree (A/T ratio) to maintain a constant relationship between the primary-air quantity and the heating requirements of each space fulfills this need. The A/T ratio determines the primary-air temperature and changeover point, and is fundamental to proper design and operation of a two-pipe system.

Transmission per Degree. The relative heating requirement of every space is determined by calculating the transmission heat flow per degree temperature difference between the space temperature and the outside temperature (assuming steady-state heat transfer). This is the sum of the (1) glass heat transfer coefficient times the glass areas, (2) wall heat transfer coefficient times the wall area, and (3) roof heat transfer coefficient times the roof area.

Air-to-Transmission (A/T) Ratio. The A/T ratio is the ratio of the primary airflow to a given space divided by the transmission per degree of that space: A/T ratio = Primary air/Transmission per degree.

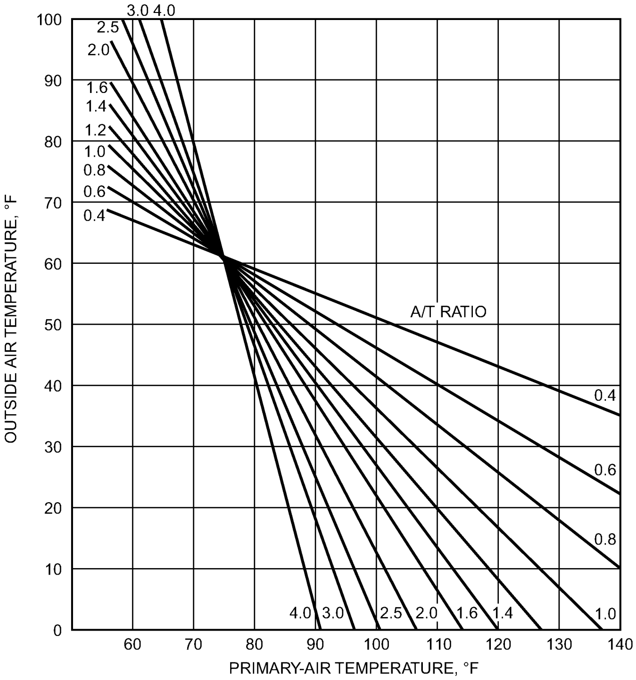
Spaces on a common primary-air zone must have approximately the same A/T ratios. The design base A/T ratio establishes the primary-air reheat schedule during intermediate seasons. Spaces with A/T ratios higher than the design base A/T ratio tend to be overcooled during light cooling loads at an outside temperature in the 70 to 90°F range, whereas spaces with an A/T ratio lower than design lack sufficient heat during the 40 to 60°F outside temperature range when primary air is warm for heating and secondary water is cold for cooling.

The minimum primary-air quantity that satisfies the requirements for ventilation, dehumidification, and both summer and winter cooling is used to calculate the minimum A/T ratio for each space. If the system operates with primary-air heating during cold weather, the heating capacity can also be the primary-air quantity determinant for two-pipe systems.

The design base A/T ratio is the highest A/T ratio obtained, and the primary airflow to each space is increased as required to obtain a uniform A/T ratio in all spaces. An alternative approach is to locate the space with the highest A/T ratio requirement by inspection, establish the design base A/T ratio, and obtain the primary airflow for all other spaces by multiplying this A/T ratio by the transmission per degree of all other spaces.

For each A/T ratio, there is a specific relationship between outside air temperature and temperature of the primary air that maintains the room at 72°F or more during conditions of minimum room cooling load. Figure 7 illustrates this variation based on an assumed minimum room load equivalent to 10°F times the transmission per degree. A primary-air temperature over 122°F at the unit is seldom used. The reheat schedule should be adjusted for hospital rooms or other applications where a higher minimum room temperature is desired, or where a space has no minimum cooling load.

Deviation from the A/T ratio is sometimes permissible. A minimum A/T ratio equal to 0.7 of the maximum A/T is suitable, if the building is of massive construction with considerable heat storage effect (Carrier 1965). The heating performance when using warm primary air becomes less satisfactory than that for systems with a uniform A/T ratio. Therefore, systems designed for A/T ratio deviation should be suitable for changeover to warm secondary water for heating whenever the outside temperature falls below 40°F. A/T ratios should be more closely maintained on buildings with large



Note: These temperatures are required at the units, and thermostat settings must be adjusted to allow for duct heat gains or losses. Temperatures are based on

1. Minimum average load in the space, equivalent to 10°F multiplied by the transmission per degree.
2. Preventing the room temperature from dropping below 72°F. These values compensate for the radiation and convection effect of the cold outside wall.

Fig. 7 Primary-Air Temperature Versus Outside

glass areas or with curtain wall construction, or on systems with low changeover temperature.

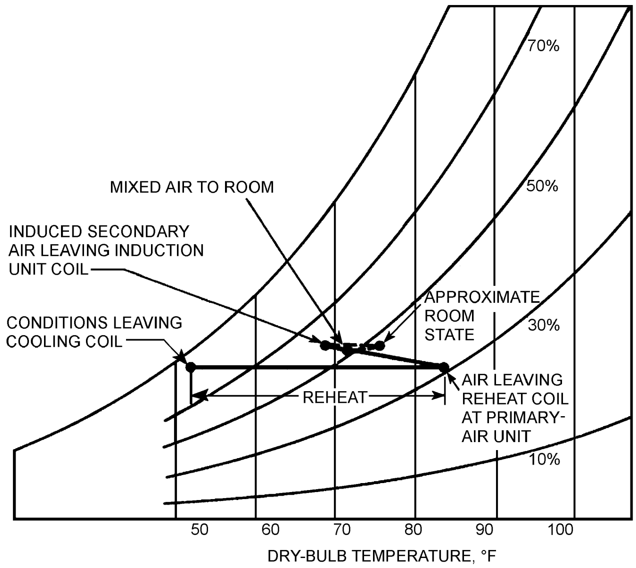
Changeover Temperature Considerations

Transition from summer operations to intermediate-season operation is done by gradually raising the primary-air temperature as the outside temperature falls, to keep rooms with small cooling loads from becoming too cold. The secondary water remains cold during both summer and intermediate seasons. Figure 8 illustrates the psychrometrics of summer operation near the changeover temperature. As the outside temperature drops further, the changeover temperature is reached. The secondary-water system can then be changed over to provide hot water for heating.

If the primary airflow is increased to some spaces to elevate the changeover temperature, the A/T ratio for the reheat zone is affected. Adjustments in primary-air quantities to other spaces on that zone will probably be necessary to establish a reasonably uniform ratio.

System changeover can take several hours and usually temporarily upsets room temperatures. Good design, therefore, includes provision for operating the system with either hot or cold secondary water over a range of 15 to 20°F below the changeover point. This range makes it possible to operate with warm air and cold secondary water when the outside temperature rises above the daytime changeover temperature. Changeover to hot water is limited to times of extreme or protracted cold weather.

Optional hot- or cold-water operation below the changeover point is provided by increasing the primary-air reheater capacity to provide adequate heat at a colder outside temperature. Figure 9 shows temperature variation for a system operating with changeover,



Note: Based on A/T ratio = 1.2, 52°F outside, reheat schedule on.

Fig. 8 Psychrometric Chart, Two-Pipe System, Off-Season Cooling

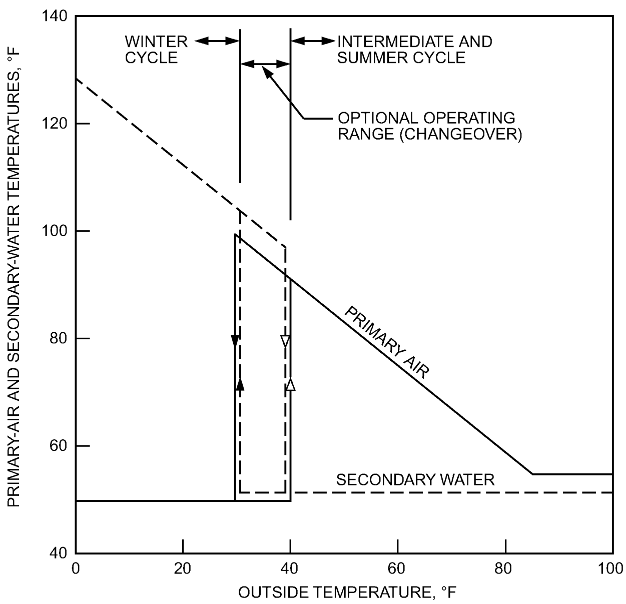


Fig. 9 Typical Changeover System Temperature Variation

indicating the relative temperature of the primary air and secondary water throughout the year and the changeover temperature range. The solid arrows show the temperature variation when changing over from the summer to the winter cycle. The open arrows show the variation when going from the winter to the summer cycle.

Nonchangeover Design

Nonchangeover systems should be considered to simplify operation for buildings with mild winter climates, or for south exposure zones of buildings with a large winter solar load. A nonchangeover system operates on an intermediate-season cycle throughout the heating season, with cold secondary water to the terminal unit coils and with warm primary air satisfying all the heating requirements. Typical temperature variation is shown in Figure 10.

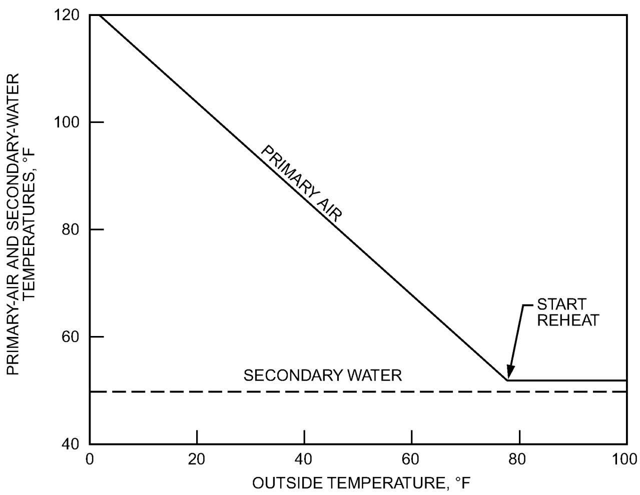


Fig. 10 Typical Nonchangeover System Variations

Spaces may be heated during unoccupied hours by operating the primary-air system with 100% return air. This feature is necessary because nonchangeover design does not usually include the ability to heat the secondary water. In addition, cold secondary water must be available throughout the winter. Primary-air duct insulation and observance of close A/T ratios for all units are essential for proper heating during cold weather.

Zoning

A two-pipe system can provide good temperature control most of the time, on all exposures during the heating and cooling seasons. Operating cost can be improved by zoning

- Primary air to allow different A/T ratios on different exposures
- Primary air to allow solar compensation of primary-air temperature
- Both air and water to allow a different changeover temperature for different exposures

All spaces on the same primary-air zone must have the same A/T ratio. The minimum A/T ratios often are different for spaces on different solar exposures, thus requiring the primary-air quantities on some exposures to be increased if they are placed on a common zone with other exposures. The primary-air quantity to units serving spaces with less solar exposure can usually be reduced by using separate primary-air zones with different A/T ratios and reheat schedules. Primary-air quantity should never be reduced below minimum ventilation requirements.

The peak cooling load for the south exposure occurs during fall or winter when outside temperatures are lower. If shading patterns from adjacent buildings or obstructions are not present, primary-air zoning by solar exposure can reduce air quantities and unit coil sizes on the south. Units can be selected for peak capacity with cold primary air instead of reheated primary air. Primary-air zoning and solar compensators save operating cost on all solar exposures by reducing primary-air reheat and secondary-water refrigeration penalty.

Separate air and water zoning may save operating cost by allowing spaces with less solar exposure to operate on the winter cycle with warm secondary water at outside temperatures as high as 60°F during the heating season. Systems with a common secondary-water zone must operate with cold secondary water to cool heavier solar exposures. Primary airflow can be lower because of separate A/T ratios, resulting in reheat and refrigeration cost savings.

Room Control

When room temperature rises, the thermostat must increase the output of the cold secondary coil (in summer) or decrease the output of the warm secondary coil (in winter). Changeover from cold to hot water in the unit coils requires changing the action of the room temperature control system. Room control for nonchangeover systems does not require the changeover action, unless it is required to provide gravity heating during shutdown.

Evaluation

Characteristics of two-pipe in-room terminal unit systems include the following:

- Usually less expensive to install than four-pipe systems
- Less capable of handling widely varying loads or providing a widely varying choice of room temperatures than four-pipe systems
- Present operational and control changeover problems, increasing the need for competent operating personnel
- More costly to operate than four-pipe systems

Electric Heat for Two-Pipe Systems

Electric heat can be supplied with a two-pipe in-room terminal unit system by a central electric boiler and hot-water terminal coils, or by individual electric-resistance heating coils in the terminal units. One method uses small electric-resistance terminal heaters for intermediate-season heating and a two-pipe changeover chilled-water/hot-water system. The electric terminal heater heats when outside temperatures are above 40°F, so cooling can be kept available with chilled water in the chilled-water/hot-water system. System or zone reheating of primary air is greatly reduced or eliminated entirely. When the outside temperature falls below this point, the chilled-water/hot-water system is switched to hot water, providing greater heating capacity. Changeover is limited to a few times per season, and simultaneous heating/cooling capacity is available, except in extremely cold weather, when little, if any, cooling is needed. If electric-resistance terminal heaters are used, they should be prevented from operating whenever the secondary-water system is operated with hot water.

Another method is to size electric resistance terminal heaters for the peak winter heating load and operate the chilled-water system as a nonchangeover cooling-only system. This avoids the operating problem of chilled-water/hot-water system changeover. In fact, this method functions like a four-pipe system, and, in areas where the electric utility establishes a summer demand charge and has a low unit energy cost for high winter consumption, it may have a lower life-cycle cost than hydronic heating with fossil fuel. A variation, especially appropriate for well-insulated office buildings with induction units where cooling is needed in perimeter offices for almost all occupied hours because of internal heat gain, is to use electric heaters in the terminal unit during occupied hours and to provide heating during unoccupied hours by raising primary-air temperature on an outside reset schedule.

FOUR-PIPE SYSTEMS

Four-pipe systems have a chilled-water supply, chilled-water return, hot-water supply, and hot-water return. The terminal unit usually has two independent secondary-water coils: one served by hot water, the other by cold water. The primary air is cold and remains at the same temperature year-round. During peak cooling and heating, the four-pipe system performs in a manner similar to the two-pipe system, with essentially the same operating characteristics. Between seasons, any unit can be operated at any level from maximum cooling to maximum heating, if both cold and warm water are being circulated, or between these extremes without regard to other units' operation.

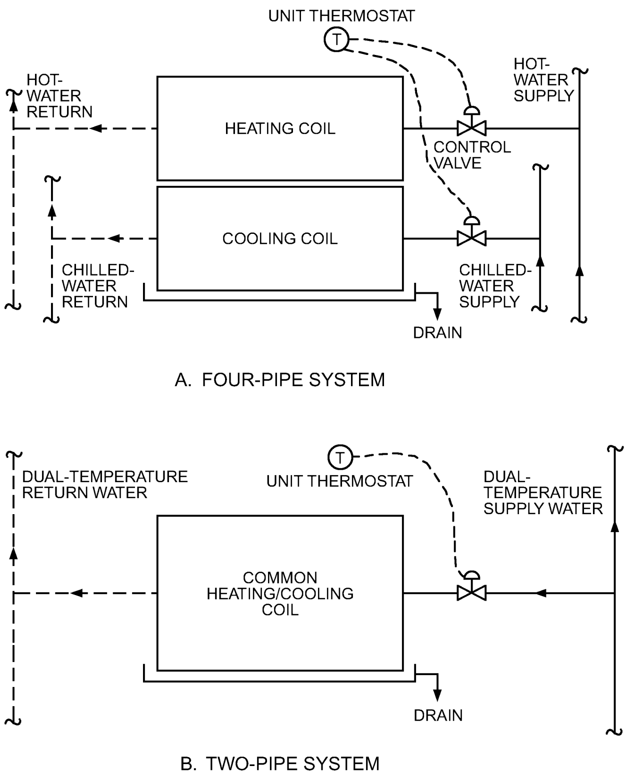


Fig. 11 Fan-Coil Unit Control

In-room terminal units are selected by their peak capacity. The A/T ratio does not apply to four-pipe systems. There is no need to increase primary-air quantities on units with low solar exposure beyond the amount needed for ventilation and to satisfy cooling loads. The available net cooling is not reduced by heating the primary air. The changeover point is still important, though, because cooling spaces on the sunny side of the building may still require secondary-water cooling to supplement the primary air at low outside temperatures.

Because primary air is supplied at a constant cool temperature at all times, it is sometimes feasible for fan-coil unit systems to extend the interior system supply to the perimeter spaces, eliminating the need for a separate primary-air system. The type of terminal unit and characteristics of the interior system are determining factors.

Zoning

Zoning primary-air or secondary-water systems is not required with four-pipe systems. All terminal units can heat or cool at all times, as long as both hot and cold secondary pumps are operated and sources of heating and cooling are available.

Room Control

The four-pipe terminal usually has two completely separated secondary-water coils: one receiving hot water and the other receiving cold water. The coils are operated in sequence by the same thermostat; they are never operated simultaneously. The unit receives either hot or cold water in varying amounts, or else no flow is present, as shown in Figure 11A. Adjustable, dead-band thermostats further reduce operating cost.

Figure 11B illustrates another unit and control configuration. A single secondary-water coil at the unit and three-way valves located at the inlet and outlet admit water from either the hot- or cold-water supply, as required, and divert it to the appropriate return pipe. This arrangement requires a special three-way modulating valve, originally developed for one form of the three-pipe system. It controls the hot or cold water selectively and proportionally, but does not mix the streams. The valve at the coil outlet is a two-position valve open to either the hot or cold water return, as required.

Overall, the two-coil arrangement provides a superior four-pipe system. Operation of the induction and fan-coil unit controls is the same year-round.

Evaluation

Compared to the two-pipe system, the four-pipe air-and-water system has the following characteristics:

- More flexible and adaptable to widely differing loads, responding quickly to load changes
- Simpler to operate
- Operates without the summer-winter changeover and primary-air reheat schedule
- Efficiency is greater and operating cost is lower, though initial cost is generally higher
- Can be designed with no interconnection of hot- and cold-water secondary circuits, and the secondary system can be completely independent of the primary-water piping

SECONDARY-WATER DISTRIBUTION

Secondary-water system design applies to induction and fan-coil systems. The secondary-water system includes the part of the water distribution system that circulates water to room terminal units when the water has been cooled or heated either by extraction from or heat exchange with another source in the primary circuit. In the primary circuit, water is cooled by flow through a chiller or is heated by a heat input source. Primary water is limited to the cooling cycle and is the source of the secondary-water cooling. Water flow through the unit coil performs secondary cooling when the room air (secondary air) gives up heat to the water. Secondary-water system design differs for two- and four-pipe systems. Secondary-water systems are discussed in Chapter 12.

AUTOMATIC CONTROLS AND BUILDING MANAGEMENT SYSTEMS

Basic HVAC system controls are available in electric, pneumatic, or electronic control systems. Depending on the application, a simple, basic system strategy may be a cost-effective solution to an owner's heating, ventilation, and cooling needs. Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* and Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals* discuss automatic control in more detail.

The next level of HVAC system management is **direct digital control (DDC),** with either pneumatic or electric control damper and valve actuators. This automatic control enhancement may include energy monitoring and energy management software, and may also be accessible off-site by modem. Building size has little to no effect on modern computerized controls: programmable controls can be furnished on the smallest HVAC equipment for the smallest projects. Chapter 41 of the 2007 *ASHRAE Handbook—HVAC Applications* covers building operating dynamics.

Automatic controls can be prepackaged and prewired on the HVAC equipment. In system analysis and selection, the design engineer should compare purchasing a prepackaged versus a traditional building automation system (BAS). HVAC controls must be compatible with other new and existing automatic controls. Chapter 39 of the 2007 *ASHRAE Handbook—HVAC Applications* discusses computer applications, and ASHRAE *Standard* 135 discusses interfacing building automation systems.

Using computers and proper software, the design engineer and building manager can provide complete facility management. A comprehensive building management system may include HVAC system control, energy management, operation and maintenance management, medical gas system monitoring, fire alarm, security, lighting control, and other reporting and trending software. This system may also be integrated and accessible from the owner's computer network and the Internet.

The building management system is an important factor in choosing the optimum HVAC system. It can be as simple as a time clock to start and stop equipment, or as sophisticated as a computerized building automation system serving a decentralized HVAC system, multiple building systems, central plant system, and/or a large campus. With a focus on energy management, the building management system can be an important business tool in achieving sustainable facility management success that begins with the System Selection Matrix selection, recommendation, and implementation.

MAINTENANCE MANAGEMENT SYSTEMS

Whereas building management systems focus on HVAC system operation, as well as electrical, plumbing, and other system operation, maintenance management systems focus on maintaining the assets, which include the mechanical and electrical systems along with the building structure, custodial, etc. A rule of thumb is that 20% of the cost of the building is in first cost, with the other 80% in operation, maintenance, and rejuvenation of the building and systems over the life of the building. During initial selection of an HVAC system, maintenance management systems should be considered for HVAC systems with an estimated long useful service life.

A **computerized maintenance management software (CMMS)** system can include an equipment database, parts and material inventory, project management software, labor records, and other relevant information for management of the building. The CMMS system also can integrate computer-aided drawing (CAD), digital photography and audio/video systems, and other proactive facility management systems that an owner may want or need for efficient and effective building management. Interfacing the building management system with the maintenance management system by specifying automatic control monitoring and trending helps the CMMS provide predictive, preventive, and real-time maintenance guidance.

BUILDING SYSTEM COMMISSIONING

With most in-room terminal units, prepackaged automatic controls may use a different automatic control checkout process than traditional control contractors. When commissioning a building system that integrates an independent control system with individual packaged control systems, commissioning can be more cumbersome because both control contractors need to participate. It is also important to obtain the control contractors' individual point checkout sheets, program logic, and list of points that require confirmation with another trade (e.g., fire alarm system installer) before the commissioning performance demonstration.

Frequently in new construction and expansion of existing installations, in-room equipment is installed in phases, requiring multiple commissioning efforts based on the construction schedule and owner occupancy. During the warranty phase, system performance should be measured, benchmarked, and course-corrected to ensure achievement of design intent. If an energy analysis study is performed as part of the comparison between decentralized and centralized concepts and/or life cycle comparison of the study is part of a LEED™ project, the resulting month-to-month energy data should be a good electronic document to benchmark actual energy consumption.

Ongoing commissioning or periodic recommissioning further ensures the original design intent is met, as well as reliable delivery of cooling and heating production. Recommissioning should be considered whenever the facility is expanded or an additional connection made to the existing systems.

Testing, adjusting, and balancing (TAB), performed during commissioning and periodically over the building's life, also contributes to successful operation and maintenance. When completing the TAB and commissioning, consider posting laminated system flow diagrams at or adjacent to the cooling and heating equipment, indicating operating instructions, TAB performance, commissioning functional performance test procedures, and emergency shutoff procedures. These documents should also be filed electronically in the building manager's computer server for quick reference.

Original basis of design and design criteria should be posted as a reminder of design intent, and be readily available in case troubleshooting, expansion, or modernization is needed.

As with all HVAC applications, for design success, building commissioning should include the system training requirements necessary for building management staff to efficiently take ownership and operate and maintain the HVAC systems over the useful service life of the installation.

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