CHAPTER 4

AIR HANDLING AND DISTRIBUTION

VERY early in the design of a new or retrofit building project, the HVAC design engineer must analyze and ultimately select the basic systems, as discussed in Chapter 1, and whether production of primary heating and cooling should be decentralized (see Chapter 2) or central (see Chapter 3). This chapter covers the options, processes, available equipment, and challenges of all-air systems; for all-water, air-and-water, and local terminal systems, see Chapter 5.

Building air systems can be designed to provide complete sensible and latent cooling, preheating, and humidification capacity in air supplied by the system. No additional cooling or humidification is then required at the zone, except for certain industrial systems. Heating may be accomplished by the same airstream, either in the central system or at a particular zone. In some applications, heating is accomplished by a separate heat source. The term *zone* implies the provision of, or the need for, separate thermostatic control, whereas the term *room* implies a partitioned area that may or may not require separate control.

The basic all-air system concept is to supply air to the room at conditions such that the sensible and latent heat gains in the space, when absorbed by supply air flowing through the space, bring the air to the desired room conditions. Because heat gains in the space vary with time, a mechanism to vary the energy removed from the space by the supply air is necessary. There are two such basic mechanisms: (1) vary the amount of supply air delivered to the space by varying the flow rate or supplying air intermittently; or (2) vary the temperature of air delivered to the space, either by modulating the temperature or conditioning the air intermittently.

All-air systems may be adapted to many applications for comfort or process work. They are used in buildings of all sizes that require individual control of multiple zones, such as office buildings, schools and universities, laboratories, hospitals, stores, hotels, and even ships. All-air systems are also used virtually exclusively in special applications for close control of temperature, humidity, space pressure, and/or air quality, including cleanrooms, computer rooms, hospital operating rooms, research and development facilities, and many industrial/manufacturing facilities.

Advantages

- Operation and maintenance of major equipment can be performed in an unoccupied area (e.g., a central mechanical room). It also maximizes choices of filtration equipment, vibration and noise control, humidification options, and the selection of high-quality and durable equipment.
- Piping, electrical equipment, wiring, filters, and vibration- and noise-producing equipment are away from the conditioned area, minimizing (1) disruption for service needs and (2) potential harm to occupants, furnishings, and processes.
- These systems offer the greatest potential for using outside air for economizer cooling instead of mechanical refrigeration.
- Seasonal changeover is simple and adapts readily to automatic control.
- A wide choice of zoning, flexibility, and humidity control under all operating conditions is possible. Simultaneous heating of one zone and cooling of another zone during off-season periods is available.
- Air-to-air and other heat recovery may be readily incorporated.
- Designs are flexible for optimum air distribution, draft control, and adaptability to varying local requirements.
- The systems are well-suited to applications requiring unusual exhaust or makeup air quantities (negative or positive pressurization, etc.).
- All-air systems adapt well to winter humidification.
- All-air systems take advantage of load diversity. In other words, a central air-handling unit serving multiple zones needs to be sized only for the peak coincident load, not the sum of the peak loads of each individual zone. In buildings with significant fenestration loads, diversity can be significant, because the sun cannot shine on all sides of a building simultaneously.
- By increasing the air change rate and using high-quality controls, these systems can maintain the closest operating condition of ±0.25°F dry bulb and ±0.5% rh. Today, some systems can maintain essentially constant space conditions.
- Removal and disposal of cold condensate from cooling coils, and capture and return of steam condensate from heating coils, is generally simpler and more practical in an all-air system.

Disadvantages

- Ducts installed in ceiling plenums require additional duct clearance, sometimes reducing ceiling height and/or increasing building height. In retrofits, these clearances may not be available.
- Larger floor plans may be necessary to allow adequate space for vertical shafts (if required for air distribution). In a retrofit application, shafts may be impractical.
- In commercial buildings, air-handling equipment rooms represent nonrentable or non-revenue-generating spaces.
- Accessibility to terminal devices, duct-balancing dampers, etc., requires close cooperation between architectural, mechanical, and structural designers.
- Air balancing, particularly on large systems, can be cumbersome.
- Permanent heating is not always available sufficiently early to provide temporary heat during construction.
- Mechanical failure of a central air-handling component, such as a fan or a cooling-coil control valve, affects all zones served by that unit.

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Heating and Cooling Calculations

Basic calculations for airflow, temperatures, relative humidity, loads, and psychrometrics are covered in Chapters 6 and 30 of the 2005 *ASHRAE Handbook—Fundamentals*. System selection should be related to the need, as indicated by the load characteristics. The designer should understand the operation of system components, their relationship to the psychrometric chart, and their interaction under various operating conditions and system configurations. The design engineer must properly determine an air-handling system's required supply air temperature and volume; outside air requirements; desired space pressures; heating and cooling coil capacities; humidification and dehumidification capacities; return, relief, and exhaust air volume requirements; and required pressure capabilities of the fan(s).

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

Zoning

Exterior zones are affected by weather conditions (e.g., wind, temperature, sun) and, depending on the geographic area and season, may require both heating and cooling at different times. The system must respond to these variations. The need for separate perimeter zone heating is determined by the following:

- Severity of heating load (i.e., geographic location)
- Nature and orientation of building envelope
- Effects of downdraft at windows and radiant effect of cold glass surfaces (i.e., type of glass, area, height, U-factor)
- Type of occupancy (i.e., sedentary versus transient).
- Operating costs (i.e., in buildings such as offices and schools that are unoccupied for considerable periods, fan operating cost can be reduced by heating with perimeter radiation during unoccupied periods rather than operating the main or local unit supply fans.)

Separate perimeter heating can operate with any all-air system. However, its greatest application has been in conjunction with VAV systems for cooling-only service. Careful design must minimize simultaneous heating and cooling. See the section on Variable Air Volume for further details.

Interior spaces have relatively constant conditions because they are isolated from external influences. Cooling loads in interior zones may vary with changes in the operation of equipment and appliances in the space and changes in occupancy, but usually interior spaces require cooling throughout the year. A VAV system has limited energy advantages for interior spaces, but it does provide simple temperature control. Interior spaces with a roof exposure, however, may require treatment similar to perimeter spaces that require heat.

Space Heating

Although steam is an acceptable medium for central system preheat or reheat coils, low-temperature hot water provides a simple and more uniform means of perimeter and general space heating. Individual automatic control of each terminal provides the ideal space comfort. A control system that varies water temperature inversely with the change in outside temperature provides water temperatures that produce acceptable results in most applications. For best results, the most satisfactory ratio can be set after installation is completed and actual operating conditions are ascertained.

Multiple perimeter spaces on one exposure served by a central system may be heated by supplying warm air from the central system. Areas with heat gain from lights and occupants and no heat loss require cooling in winter, as well as in summer. In some systems, very little heating of return and outside air is required when the space is occupied. Local codes dictate the amount of outside air required (see ASHRAE *Standard* 62.1 for recommended optimum outside air ventilation). For example, with return air at 75°F and outside air at 0°F, the temperature of a 25% outside/75% return air mixture would be 56°F, which is close to the temperature of air supplied to cool such a space in summer. In this instance, a preheat coil installed in the minimum outside airstream to warm outside air can produce overheating, unless it is sized so that it does not heat the air above 35 to 40°F. Assuming good mixing, a preheat coil in the mixed airstream prevents this problem. The outside air damper should be kept closed until room temperatures are reached during warm-up. A return air thermostat can terminate warm-up.

When a central air-handling unit supplies both perimeter and interior spaces, supply air must be cool to handle interior zones. Additional control is needed to heat perimeter spaces properly. Reheating the air is the simplest solution, but is not acceptable under most energy codes. An acceptable solution is to vary the volume of air to the perimeter and to combine it with a terminal heating coil or a separate perimeter heating system, either baseboard, overhead air heating, or a fan-powered terminal unit with supplemental heat. The perimeter heating should be individually controlled and integrated with the cooling control. Lowering the supply water temperature when less heat is required generally improves temperature control. For further information, refer to Chapter 12 in this volume and Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Air Temperature Versus Air Quantity

Designers have considerable flexibility in selecting supply air temperature and corresponding air quantity within the limitations of the procedures for determining heating and cooling loads. The difference between supply air temperature and desired room temperature is often referred to as the ΔT of the all-air system. The relationship between ΔT and air quantity (by volume) is approximately linear and inverse: doubling the ΔT results in halving of the air quantity. ASHRAE *Standard* 55 addresses the effect of these variables on comfort.

The traditional all-air system is typically designed to deliver approximately 55°F supply air, for a conventional building with a desired indoor temperature of approximately 75°F. That supply air temperature is commonplace because the air is low enough in absolute moisture to result in reasonable space relative humidity in conventional buildings with modest latent heat loads. However, lower supply air temperatures may be required in spaces with high latent loads, such as gymnasiums or laundries, and higher supply air temperatures can be applied selectively with caution. Obviously, not all buildings are conventional or typical, and designers are expected not to rely on these conventions unquestioningly. Commercially available load calculation software programs, when applied correctly, help the designer find the optimum supply air temperature for each application.

In cold air-systems, the supply air temperature is designed significantly lower than 55°F (perhaps as low as 44°F) in an effort to reduce the size of ducts and fans. In establishing supply air temperature, the initial cost of lower airflow and low air temperature (smaller fan and duct systems) must be calculated against potential problems of distribution, condensation, air movement, and decreased removal of odors and gaseous or particulate contaminants. Terminal devices that use low-temperature air can reduce the air distribution cost. These devices mix room and primary air to maintain reasonable air movement in the occupied space. Because the amount of outside air needed is the same for any system, the percentage in low-temperature systems is high, requiring special care in design to avoid freezing preheat or cooling coils.

Advantages of cold-air systems include lower humidity levels in the building, because colder air has a lower maximum absolute moisture content, and reduced fan energy consumption. However, these low-temperature air supply systems might actually increase overall building energy consumption, because the cold-air process strips more moisture from the air (i.e., greater latent heat removal) than is otherwise required in comfort applications. Again, commercially

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available software can help the designer evaluate the overall energy effects of these decisions.

Space Pressure

Designers faced with the need to provide space pressure control along with temperature, humidity, and/or air filtration control will most likely find that all-air systems are the only systems capable of achieving this pressure control. Many special applications, such as isolation rooms, research labs, and cleanrooms, require constant-volume supply and exhaust air to the space to ensure space pressure control. Some of these applications allow the designer to consider reduced air volume during unoccupied periods while still maintaining space pressure control.

Variable-air-volume (VAV) space pressure control is another way to ensure constant space pressure. In addition to individual rooms with fixed positive or negative pressure, entire areas and/or floors may require space pressure control, with individual rooms set for one condition and adjacent areas and/or corridors with opposite space pressure control, so that the entire area is air-balanced to a recommended, slightly positive pressure. With each of these applications, the testing, adjusting, and balancing firm plays an important role in the commissioning process.

Other Considerations

All-air systems operate by maintaining a temperature differential between the supply air and the space. Any load that affects this differential and the associated airflow must be calculated and considered, including the following:

- All **fans** (supply, return, and supplemental) add heat. All of the fan shaft power eventually converts to heat in the system, either initially as fan losses or downstream as duct friction losses. Motor inefficiencies are an added load if that motor is in the airstream. Whether the fan is upstream of the cooling coil (blow-through) or downstream (draw-though) affects how this load must be accounted for. The effect of these gains can be considerable, particularly in process applications. Heat gain in medium-pressure systems is about 0.5°F per inch of water static pressure.
- The **supply duct** may gain or lose heat from the surroundings. Most energy codes require that the supply duct be insulated, which is usually good practice regardless of code requirements. Uninsulated supply ducts delivering cool air are subject to condensation formation, leading to building water damage and potential mold growth, depending on the dew-point temperature of surrounding air.
- Controlling **humidity** in a space can affect the air quantity and become the controlling factor in selecting supply airflow rate. VAV systems provide only limited humidity control, so if humidity is critical, extra care must be taken in design.

First, Operating, and Maintenance Costs

As with all systems, the initial cost of an air-handling system varies widely (even for identical systems), depending on location, condition of the local economy, and contractor preference. For example, a dual-duct system is more expensive because it requires essentially twice the amount of material for ducts as that of a comparable single-duct system. Systems requiring extensive use of terminal units are also comparatively expensive. The operating cost depends on the system selected, the designer's skill in selecting and correctly sizing components, efficiency of the duct design, and effect of building design and type on the operation. All-air systems can greatly minimize operating cost.

Because an all-air system separates the air-handling equipment from occupied space, maintenance on major components in a central location is more economical. Also, central air-handling equipment requires less maintenance than a similar total capacity of multiple small packaged units. The many terminal units used in an all-air system do, however, require periodic maintenance. Because these units (including reheat coils) are usually installed throughout a facility, maintenance costs for these devices must be considered.

Energy

The engineer's early involvement in the design of any facility can considerably affect 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, single-duct systems may consume less energy than dual-duct systems, and VAV systems are more energy-efficient than constant-air-volume systems. Savings from a VAV system come from the savings in fan power and because the system does not overheat or overcool spaces, and reheat is minimized.

The air distribution system for an all-air system consists of two major subsystems: (1) air-handling units that generate conditioned air under sufficient positive pressure to circulate it to and from the conditioned space, and (2) a distribution system that only carries air from the air-handling unit to the space being conditioned. The air distribution subsystem often includes means to control the amount or temperature of air delivered to each space.

AIR-HANDLING UNITS

The basic air-handling system is an all-air, single-zone HVAC system consisting of an air-handling unit and an air distribution system. The air-handling unit may be designed to supply constant or variable air volume for low-, medium-, or high-velocity air distribution. Normally, the equipment is located outside the conditioned area in a basement, penthouse, or service area. It can, however, be installed in the area if conditions permit. The equipment can be adjacent to the primary heating and refrigeration equipment or at considerable distance, with refrigerant, chilled water, hot water, or steam circulated to it for energy transfer.

Figure 1 shows a typical draw-through central system that supplies conditioned air to a single zone. A blow-through configuration may also be used if space or other conditions dictate. The quantity and quality of supplied air are fixed by space requirements and determined as indicated in Chapters 29 and 30 of the 2005 *ASHRAE Handbook—Fundamentals*. Air gains and loses heat by contacting heat transfer surfaces and by mixing with air of another condition. Some of this mixing is intentional, as at the outside air intake; other mixing results from the physical characteristics of a particular component, as when untreated air passes through a coil without contacting the fins (bypass factor).

All treated and untreated air must be well mixed for maximum performance of heat transfer surfaces and for uniform temperatures

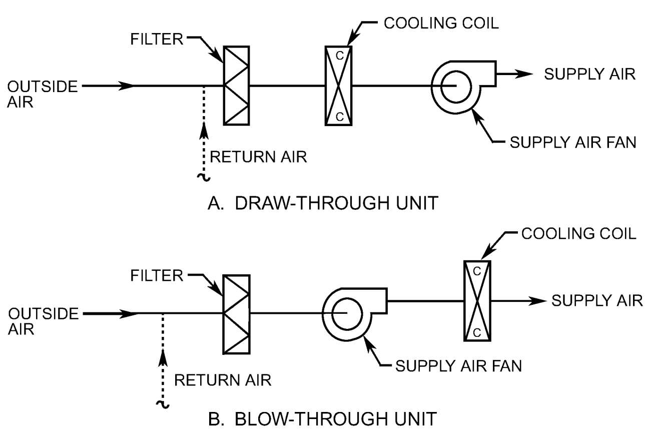

Fig. 1 Typical Air-Handling Unit Configurations
(Courtesy RDK Engineers)

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in the airstream. Stratified, parallel paths of treated and untreated air must be avoided, particularly in the vertical plane of systems using double-inlet or multiple-wheel fans. Because these fans may not completely mix the air, different temperatures can occur in branches coming from opposite sides of the supply duct.

Primary Equipment

Cooling. Either central station or localized equipment, depending on the application, can provide cooling. Most large systems with multiple central air-handling units use a central refrigeration plant. Small, individual air-handling equipment can (1) be supplied with chilled water from central chillers, (2) use direct-expansion cooling with a central condensing (cooling tower) system, or (3) be air-cooled and totally self-contained. The decision to provide a central plant or local equipment is based on factors similar to those for air-handling equipment, and is addressed in Chapters 1 to 3.

Heating. The same criteria described for cooling are usually used to determine whether a central heating plant or a local one is desirable. Usually, a central, fuel-fired plant is more desirable for heating large facilities. In small facilities, electric heating is a viable option and is often economical, particularly where care has been taken to design energy-efficient systems and buildings.

Air-Handling Equipment

Packaged air-handling equipment is commercially available in many sizes, capacities, and configurations using any desired method of cooling, heating, humidification, filtration, etc. These systems can be suitable for small and large buildings. In large systems (over 50,000 cfm), air-handling equipment is usually custom-designed and fabricated to suit a particular application. Air handlers may be either centrally or remotely located.

Air-handling units (AHUs) can be one of the more complicated pieces of equipment to specify or order, because a vast array of choices are available, and because there is no single-number identifier (e.g., a "50 ton unit" or a "40,000 cfm unit") that adequately describes the desired product. Regardless of size or type, the designer must properly determine an air-handling unit's required supply air temperature and volume; outside air requirements; desired space pressures; heating and cooling coil capacities; humidification and dehumidification capacities; return, relief, and exhaust air volume requirements; and required pressure capabilities of the fan(s). Typically, these parameters and more must be specified or scheduled by the design engineer before an installer or equipment supplier can provide an AHU.

Central Mechanical Equipment Rooms (MERs)

The type of facility and other factors help determine where the air-handling equipment is located. Central fan rooms are more common in laboratory or industrial facilities, where maintenance is isolated from the conditioned space. Reasons a design engineer may consider a central air-handling unit, or bank of central air-handling units, include the following:

- Fewer total pieces of equipment to maintain
- Maintenance is concentrated at one location
- Energy recovery opportunities may be more practical
- Vibration and noise control, seismic bracing, outside air intakes, economizers, filtration, humidification, and similar auxiliary factors may be more straightforward when equipment is centralized

Decentralized MERs

Many office buildings locate air-handling equipment at each floor, or at other logical subdivisions of a facility. Reasons a design engineer may consider multiple distributed air-handling unit locations include the following:

- Reduced size of ducts reduces space required for distribution ductwork and shafts.
- Reduced equipment size as a result of decentralized systems allows use of less expensive packaged equipment and reduces the necessary sophistication of training for operating and maintenance personnel.
- For facilities with varied occupancy, multiple decentralized air-handling units can be set back or turned off in unoccupied areas.
- Failure of an air-handling unit affects only the part of the building served by that one unit.

Fans

Both packaged and built-up air-handling units can use any type of fan. Centrifugal fans may be forward-curved, backward-inclined, or airfoil, and single-width/single-inlet (SWSI) or double-width/double-inlet (DWDI). Many packaged air-handlers feature a single fan, but it is possible for packaged and custom air handlers to use multiple DWDI centrifugal fans on a common shaft with a single drive motor. SWSI centrifugal plug fans without a scroll are sometimes used on larger packaged air handlers to make them more compact. Vaneaxial fans, both adjustable- and variable-pitch during operation, are often used on very large air-handling units. Fan selection should be based on efficiency and sound power level throughout the anticipated range of operation, as well as on the ability of the fan to provide the required flow at the anticipated static pressure. Chapter 20 further discusses fans and fan selection.

AIR-HANDLING UNIT PSYCHROMETRIC PROCESSES

Cooling

The basic methods used for cooling and dehumidification include the following:

- **Direct expansion** (refrigerant) takes advantage of the latent heat of the refrigerant fluid, and cools as shown in the psychrometric diagram in Figure 2.
- **Chilled-water** (fluid-filled) coils use temperature differences between the fluid and air to exchange energy by the same process as in Figure 2 (see the section on Dehumidification).
- **Direct spray of water in the airstream** (Figure 3), an adiabatic process, uses the latent heat of evaporation of water to reduce dry-bulb temperature while increasing moisture content. Both sensible and latent cooling are also possible by using chilled water. A conventional evaporative cooler uses the adiabatic process by

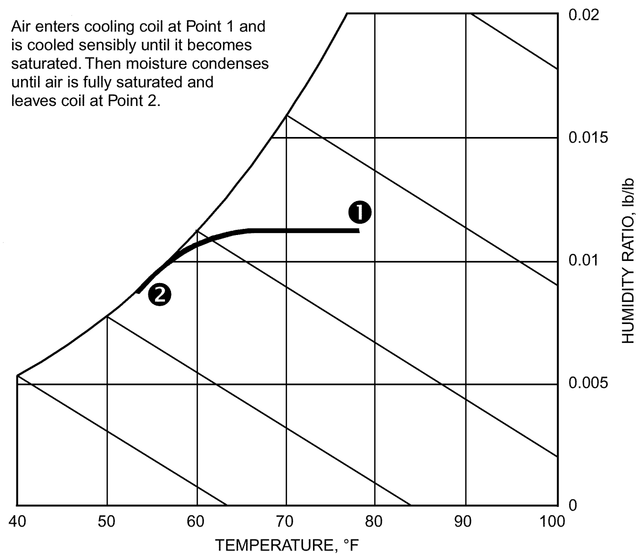

Fig. 2 Direct-Expansion or Chilled-Water Cooling and Dehumidification

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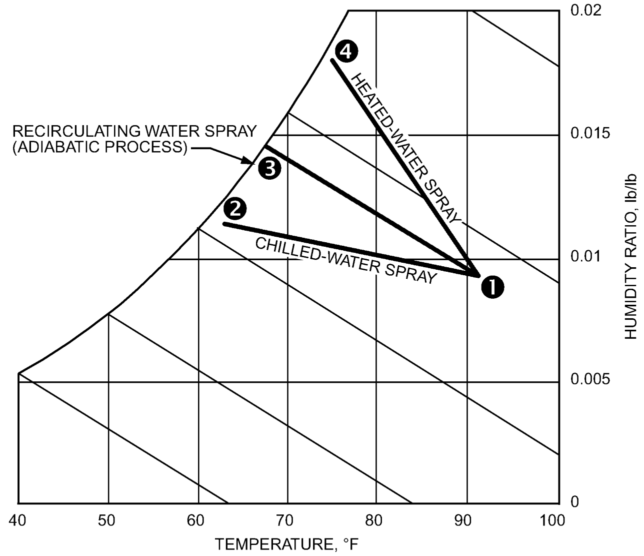

Fig. 3 Direct Spray of Water in Airstream Cooling

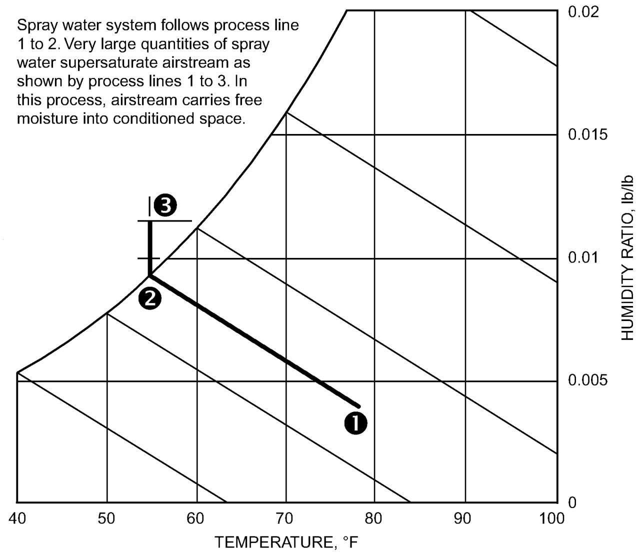

Fig. 4 Supersaturated Evaporative Cooling

spraying or dripping recirculated water onto a filter pad (see the section on Humidification).

- The **wetted duct** or **supersaturated** system is a variation of direct spray. In this system, tiny droplets of free moisture are carried by the air into the conditioned space, where they evaporate and provide additional cooling, reducing the amount of air needed for cooling the space (Figure 4).
- **Indirect evaporation** adiabatically cools outside or exhaust air from the conditioned space by spraying water, then passes that cooled air through one side of a heat exchanger. Air to be supplied to the space is cooled by passing through the other side of the heat exchanger. Chapter 40 has further information on this method of cooling.

Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals* details the psychrometric process of these methods.

Heating

The basic methods used for heating include the following:

- **Steam** uses the latent heat of the fluid.
- **Hot-water** (fluid-filled) coils use temperature differences between the warm fluid and the cooler air.
- **Electric heat** also uses the temperature difference between the heating coil and the air to exchange energy.
- **Direct or indirect gas- or oil-fired heat exchangers** can also be used to add sensible heat to the airstream.

The effect on the airstream for each of these processes is the same and is shown in Figure 5. For basic equations, refer to Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals*.

Humidification

Methods used to humidify air include the following:

- **Direct spray of recirculated water** into the airstream (air washer) reduces the dry-bulb temperature while maintaining an almost constant wet bulb, in an adiabatic process (see Figure 3, path 1 to 3). The air may also be cooled and dehumidified, or heated and humidified, by changing the spray water temperature.
  In one variation, the surface area of water exposed to the air is increased by spraying water onto a cooling/heating coil. The coil surface temperature determines leaving air conditions. Another method is to spray or distribute water over a porous medium, such

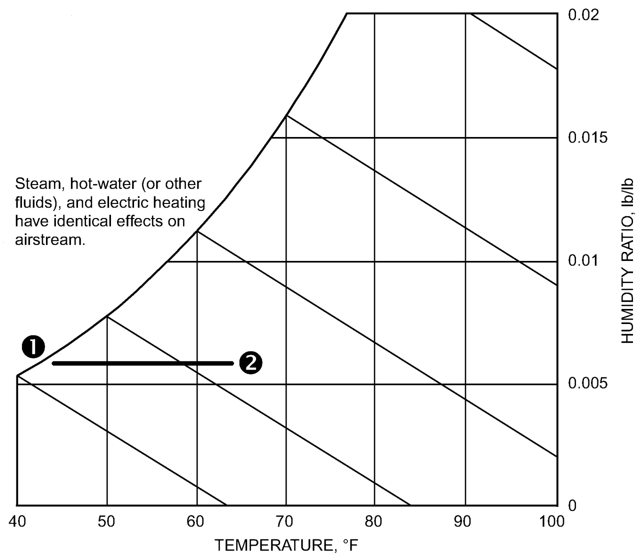

Fig. 5 Steam, Hot-Water, and Electric Heating, and Direct and Indirect Gas- and Oil-Fired Heat Exchangers

as those in evaporative coolers. This method requires careful monitoring of the water condition to keep biological contaminants from the airstream (Figure 6).
- **Compressed air** that forces water through a nozzle into the airstream is essentially a constant wet-bulb (adiabatic) process. The water must be treated to keep particles from entering the airstream and contaminating or coating equipment and furnishings. Many types of nozzles are available.
- **Steam injection** is a constant dry-bulb process (Figure 7). As the steam injected becomes superheated, the leaving dry-bulb temperature increases. If live steam is injected into the airstream, the boiler water treatment chemical must be nontoxic to occupants and nondamaging to building interior and furnishings.

Dehumidification

Moisture condenses on a cooling coil when its surface temperature is below the air's dew point, thus reducing the humidity of the

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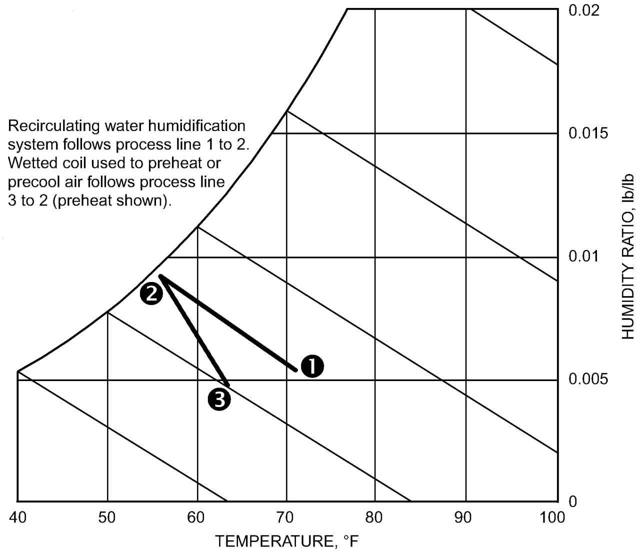

Fig. 6 Direct Spray Humidification

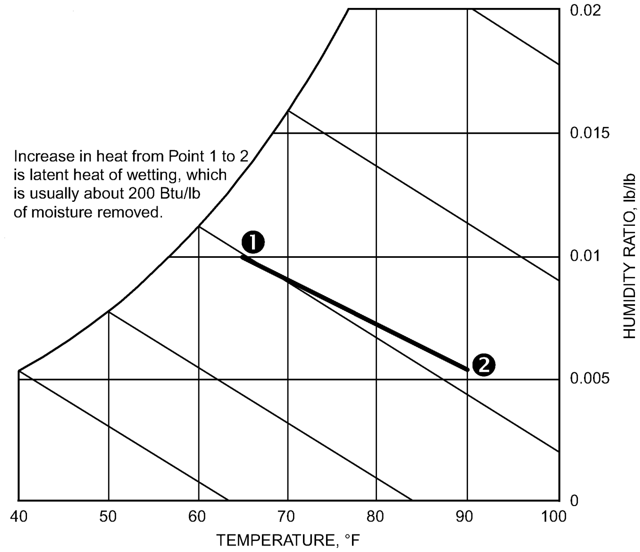

Fig. 8 Chemical Dehumidification

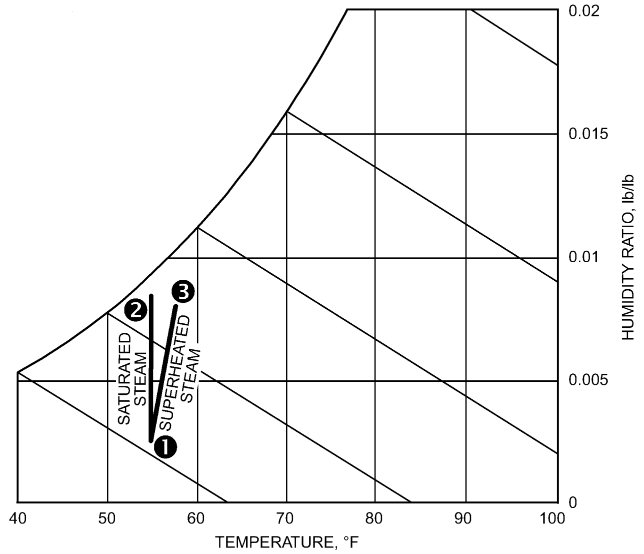

Fig. 7 Steam Injection Humidification

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air. Similarly, air will also be dehumidified if a fluid with a temperature below the airstream dew point is sprayed into the airstream (see the section on Air Washers in Chapter 40). The process is identical to that shown in Figure 2, except that the moisture condensed from the airstream condenses on, and dissolves in, the spray droplets instead of on the solid coil surface.

Chemical dehumidification involves either passing air over a solid desiccant or spraying the air with a solution of desiccant and water. Both of these processes add heat, often called the **latent heat of wetting**, to the air being dehumidified. Usually about 200 Btu/lb of moisture is removed (Figure 8). These systems should be reviewed with the user to ensure that the space is not contaminated. Chapter 23 has more information on this topic.

Air Mixing or Blending

Adiabatic mixing of two or more airstreams (e.g., outside and return air) into a common airstream can be shown on a psychrometric chart with reasonable accuracy (see Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals*).

AIR-HANDLING UNIT COMPONENTS

The following sections describe many commonly available air-handling unit components. Not all of these components will necessarily be used in any one system.

To determine the system's air-handling requirement, the designer must consider the function and physical characteristics of the space to be conditioned, and the air volume and thermal exchange capacities required. Then, the various components may be selected and arranged by considering the fundamental requirements of the central system.

Figure 1 shows one possible general arrangement of air-handling unit components for a single-zone, all-air central system suitable for year-round air conditioning. This arrangement allows close control of temperature and humidity. Although Figure 1 indicates a built-up system, most of these components are available from many manufacturers completely assembled or in subassembled sections that can be bolted together in the field. When selecting central system components, specific design parameters must be evaluated to balance cost, controllability, operating expense, maintenance, noise, and space. The sizing and selection of primary air-handling units substantially affect the results obtained in the conditioned space.

The equipment must be adequate, accessible for easy maintenance, and not overly complex in its arrangement and control to provide the required conditions. Further, the designer should consider economics in component selection. Both initial and operating costs affect design decisions. For example, the designer should not arbitrarily design for a 500 fpm face velocity, which has been common for selecting cooling coils and other components. Filter and coil selection at 300 to 400 fpm, with resultant lower pressure loss, could produce a substantial payback on constant-volume systems. Chapter 36 of the 2007 *ASHRAE Handbook—HVAC Applications* has further information on energy and life-cycle costs.

Return Air Fan

A return air fan is optional on small systems, but is essential for proper operation of air economizer systems for free cooling from outside air if the return path has a significant pressure drop (greater than approximately 0.3 in. of water). It provides a positive return and exhaust from the conditioned area, particularly when mixing dampers allow cooling with outside air in intermediate seasons and winter. The return air fan ensures that the proper volume of air returns from the conditioned space. It prevents excess building pressure when economizer cycles introduce more than the minimum quantity of outside air, and reduces the static pressure against which the supply fan must work. The return air fan should handle a slightly smaller amount of air to account for fixed exhaust systems, such as toilet exhaust, and to ensure a slight positive pressure in the conditioned space. Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* provides design details.

Relief Air Fan

In many situations, a relief (or exhaust) air fan may be used instead of a return fan. A relief air fan relieves ventilation air introduced during air economizer operation and operates only when this control cycle is in effect. When a relief air fan is used, the supply fan must be designed for the total supply and return pressure losses in the system. During economizer mode, the relief fan must be controlled to ensure a slight positive pressure in the conditioned space, as with the return air fan system. The section on Economizers describes the required control for relief air fans.

Automatic Dampers

The section on Mixing Plenums discusses conditions that must be considered when choosing, sizing, and locating automatic dampers for this critical mixing process. These dampers throttle the air with parallel- or opposed-blade rotation. These two forms of dampers have different airflow throttling characteristics (see Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals*). Pressure relationships between various sections of this mixing process must be considered to ensure that automatic dampers are properly sized for wide-open and modulating pressure drops. See ASHRAE *Guideline* 16 for additional detail.

Relief Openings

Relief openings in large buildings should be constructed similarly to outside air intakes, but may require motorized or self-acting backdraft dampers to prevent high wind pressure or stack action from causing airflow to reverse when the automatic dampers are open. Pressure loss through relief openings should be 0.10 in. of water or less. Low-leakage dampers, such as those for outside intakes, prevent rattling and minimize leakage. The relief air opening should be located so that air does not short-circuit to the outside air intake.

Return Air Dampers

Negative pressure in the outside air intake plenum is a function of the resistance or static pressure loss through the outside air louvers, damper, and duct. Positive pressure in the relief air plenum is likewise a function of the static pressure loss through the relief damper, the relief duct between the plenum and outside, and the relief louver. The pressure drop through the return air damper must accommodate the pressure difference between the positive-pressure relief air plenum and the negative-pressure outside air plenum. Proper sizing of this damper facilitates better control and mixing. An additional manual damper may be required for proper air balancing.

Outside Air Intakes

Resistance through outside air intakes varies widely, depending on construction. Frequently, architectural considerations dictate the type and style of louver. The designer should ensure that the louvers selected offer minimum pressure loss, preferably not more than 0.10 in. of water. High-efficiency, low-pressure louvers that effectively limit carryover of rain are available. Flashing installed at the outside wall and weep holes or a floor drain will carry away rain and melted snow entering the intake. Cold regions may require a snow baffle to direct fine snow to a low-velocity area below the dampers. Outside air dampers should be low-leakage types with special gasketed edges and endseals. A damper section and damper operator are strongly recommended for ensuring minimum ventilation. The maximum outside air damper controls the air needed for economizer cycles.

The location of intake and exhaust louvers should be carefully considered; in some jurisdictions, location is governed by codes. For example, if heat recovery devices are used, intake and exhaust airstreams may need to be run in parallel, such as through air-to-air plate heat exchangers. Louvers must be separated enough to avoid short-circuiting air. Furthermore, intake louvers should not be near a potential source of contaminated air, such as a boiler stack or hood exhaust. Relief air should also not interfere with other systems.

A common complaint in buildings is a lack of outside air. This is especially a concern in VAV systems in which outside air quantities are established for peak loads and are then reduced in proportion to the air supplied during periods of reduced load. A simple control added to the outside-air damper can eliminate this problem and keep the amount of outside air constant, regardless of VAV system operation. However, the need to preheat outside air must be considered if this control is added.

Also, although some codes require as little as 5 cfm per person (about 0.05 cfm/ft^2) of outside air, this amount may be too low for a building using modern construction materials. Higher outside air quantities may be required to reduce odors, volatile organic compounds (VOCs), and potentially dangerous pollutants. ASHRAE *Standard* 62.1 provides information on ventilation for acceptable indoor air quality. Air quality (i.e., control or reduction of contaminants such as VOCs, formaldehyde from furnishings, and dust) must be reviewed by the engineer.

Economizers

An air-side economizer uses outside air to reduce refrigeration requirements. Whereas a logic circuit maintains a fixed minimum of ventilation outside air in all weather, the air-side economizer is an attractive option for reducing energy costs when weather conditions allow. The air-side economizer takes advantage of cool outside air either to assist mechanical cooling or, if outside air is cool enough, to provide total system cooling. When weather permits, temperature controls systems can modulate outside air and return air in the correct proportion to produce desired supply air temperatures without the use of mechanical heating or cooling.

To exhaust the extra outside air brought in by the economizer, a method of variable-volume relief must be provided. The relief volume may be controlled by modulating the relief air dampers in response to building space pressure. Another common approach is opening the relief/exhaust and outside air intake dampers simultaneously, although this alone does not address space pressurization. A powered relief or return/relief fan may also be used. The relief system is off and relief dampers are closed when the air-side economizer is inactive.

For details on advantages and disadvantages of air-side economizers, see Chapter 2.

Mixing Plenums

Mixing plenums provide space for airstreams with different properties to mix as they are introduced into a common section of ductwork or air-handling unit, allowing the system to operate as intended. If the airstreams are not sufficiently mixed, the resulting stratification adversely affects system performance. Some problems associated with stratification are nuisance low-temperature safety cutouts, frozen cooling coils, excess energy use by the preheat coil, inadequate outside air, control hunting, and poor outside air distribution throughout occupied spaces.

A common example of a mixing plenum is the air-handling unit mixing box, in which outside and recirculated airstreams are combined. In air-handling units, mixing boxes typically have one inlet, with control dampers, for each airstream.

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There are no performance standards for mixing boxes or mixing plenums. Thus, it is difficult to know whether a particular mixing box design will provide sufficient mixing. In the absence of performance data, many rules of thumb have been developed to increase the mixing provided by mixing boxes. It is important to note that few supporting data exist; the following suggestions are based largely on common-sense solutions and anecdotal evidence:

- The minimum outside air damper should be located as close as possible to the return air damper.
- An outside air damper sized for 1500 fpm gives good control.
- Low-leakage outside air dampers minimize leakage during system shutdown.
- A higher velocity through the return air damper facilitates air balance and may increase mixing.
- Parallel-blade dampers may aid mixing. Positioning the dampers so that the return and outside airstreams are deflected toward each other may increase mixing.
- Mixing dampers should be placed across the full width of the unit, even if the location of the return duct makes it more convenient to return air through the side. Return air entering through the side of an air-handling unit can pass through one side of a double-inlet fan while outside air passes through the other side. This same situation can exist whenever two parallel fans are used in an air-handling unit receiving two different airstreams. Wherever there are two fans and two airstreams, an air mixer should be used.
- Field-built baffles may be used to create additional turbulence and to enhance mixing. Unfortunately, the mixing effectiveness and pressure drop of field-built solutions are unknown.

If stratification is anticipated in a system, then special mixing equipment that has been tested by the manufacturer (see the section on Static Air Mixers) should be specified and used in the air-handling system.

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Static Air Mixers

Static air mixers are designed to enhance mixing in the mixing plenum to reduce or eliminate problems associated with stratification. These devices have no moving parts and create turbulence in the airstream, which increases mixing. They are usually mounted between the mixing box and the heating or cooling coil; the space required depends on the amount of mixing that is required. Typical pressure loss for these devices is 0.10 to 0.30 in. of water.

There are no performance standards for air mixers. Thus, manufacturers of air mixers and air-handling units should demonstrate that their devices provide adequate mixing.

Filter Section

A system's overall performance depends heavily on the filter. Unless the filter is regularly maintained, system resistance increases and airflow diminishes. Accessibility for replacement is an important consideration in filter arrangement and location. In smaller air-handling units, filters are often placed in a slide-out rack for side-access replacement. In larger units and built-up systems with internal or front-loading access, there should be at least 3 ft between the upstream face of the filter bank and any obstruction. Other requirements for filters can be found in Chapter 28 and in ASHRAE *Standard* 52.2.

Good mixing of outside and return air is also necessary for good filter performance. A poorly placed outside air duct or a bad duct connection to the mixing plenum can cause uneven filter loading and poor distribution of air through the coil section.

Particulate filters are rated according to ASHRAE *Standard* 52.2's minimum efficiency rating value (MERV) system, a numeric ranking from 1 (least) to 20 (highest). A particulate filter bank of at least MERV 6 should be placed upstream of the first coil, to maintain coil cleanliness. Depending on the spaces served, many applications demand higher-efficiency filters. Some studies suggest filters up to MERV 14 can pay for themselves in reduced coil maintenance and better heat transfer effectiveness. Where higher-MERV filters are used, many designers specify a lower-MERV prefilter as an inexpensive sacrificial filter to capture bulk particulate and extend the life of the more expensive final filter.

The location of the filter bank(s) may be governed by codes. For example, many prevailing health care codes mandate a prefilter upstream of all fans, coils, and humidifiers, plus a final filter bank downstream of all fans, coils, and humidifiers.

Designers are not limited to particulate filters. Electronic air cleaners and gaseous-phase (e.g., activated carbon) filters are available for added protection. For example, ASHRAE *Standard* 62.1 requires use of gaseous-phase filters for certain, usually urban, regions where outside air quality has been measured to exceed threshold values for ozone or other gaseous contaminants. Odor control using activated carbon or potassium permanganate as a filter medium is also available. Chapters 12 and 13 of the 2005 *ASHRAE Handbook—Fundamentals* have more information on odor control.

Preheat Coil

Preheat coils are heating coils placed upstream of a cooling coil. Preheat coils can use steam, hot water, or electric resistance as a medium. Some air-handling units do not require a preheat coil at all, particularly if the percentage of outside air is low and if building heating is provided elsewhere (e.g., perimeter baseboard). Where used, a preheat coil should have wide fin spacing, be accessible for easy cleaning, and be protected by filters. If a preheat coil is located in the minimum outside airstream rather than in the mixed airstream as shown in Figure 1, it should not heat the air to an exit temperature above 35 to 45°F; preferably, it should become inoperative at outside temperatures above 45°F. For use with steam, inner distributing tube or integral face-and-bypass coils are preferable. Hot-water preheat coils should be piped for counterflow so that the coldest air contacts the warmest part of the coil surface first. Consider a constant-flow recirculating pump if the local climate and anticipated percentage of outside air may result in freezing conditions at a hot-water preheat coil. Chapter 26 provides more detailed information on heating coils.

Cooling Coil

Sensible and latent heat are removed from the air by the cooling coils. The cooling medium can be either chilled water or refrigerant, in which case the refrigerant coil serves as the evaporator in a vapor-compression refrigeration cycle. The psychrometrics of cooling and dehumidification were described earlier in this chapter.

In all finned coils, some air passes through without contacting the fins or tubes. The amount of this bypass can vary from 30% for a four-row coil at 700 fpm, to less than 2% for an eight-row coil at 300 fpm. The dew point of the air mixture leaving a four-row coil might satisfy a comfort installation with 25% or less outside air, a small internal latent load, and sensible temperature control only. For close control of room conditions for precision work, a deeper coil may be required. Chapter 22 provides more information on cooling coils and their selection.

Coil freezing can be a serious problem with chilled-water coils. Full-flow circulation of chilled water during freezing weather, or even reduced flow with a small recirculating pump, minimizes coil freezing and eliminates stratification. Further, continuous full-flow circulation can provide a source of off-season chilled water in air-and-water systems. Antifreeze solutions or complete coil draining also prevent coil freezing. However, because it is difficult (if not impossible) to drain most cooling coils completely, caution should be used if this option is considered.

Another design consideration is the drain pan. ASHRAE *Standard* 62.1 calls for drain pans to be sloped to a drain, to avoid holding standing water in the air-handling unit. Because of the constant presence of moisture in the cooling coil drain pan and nearby casing, many designers require stainless steel construction in that portion of the air-handling unit.

Reheat Coil

Reheat coils are heating coils placed downstream of a cooling coil. Reheat systems are strongly discouraged, unless recovered energy is used (see ASHRAE *Standard* 90.1). Reheating is limited to laboratory, health care, or similar applications where temperature and relative humidity must be controlled accurately. Heating coils located in the reheat position, as shown in Figure 1, are frequently used for warm-up, although a coil in the preheat position is preferable. Hot-water coils provide a very controllable source of reheat energy. Inner-distributing-tube coils are preferable for steam applications. Electric coils may also be used. See Chapter 26 for more information.

Humidifiers

Humidifiers may be installed as part of the air-handling unit, or in terminals at the point of use, or both. Where close humidity control of selected spaces is required, the entire supply airstream may be humidified to a low humidity level in the air handler. Terminal humidifiers in the supply ducts serving selected spaces bring humidity up to the required levels. For comfort installations not requiring close control, moisture can be added to the air by mechanical atomizers or point-of-use electric or ultrasonic humidifiers. Proper location of this equipment prevents stratification of moist air in the system.

Steam grid humidifiers with dew-point control usually are used for accurate humidity control. Air to a laboratory or other space that requires close humidity control must be reheated after leaving a cooling coil before moisture can be added. Humidifying equipment capacity should not exceed the expected peak load by more than 10%. If humidity is controlled from the room or return air, a limiting humidistat and fan interlock may be needed in the supply duct. This prevents condensation and mold or mildew growth in the ductwork. Humidifiers add some sensible heat that should be accounted for in the psychrometric evaluation. See Chapter 21 for additional information.

An important question for air-handling unit specifiers is where to place the humidification grid. Moisture cannot be successfully added to cold air, so placement is typically downstream of a preheat coil. For general building humidification, one satisfactory location is between a preheat coil and cooling coil.

Another consideration is absorption distance (i.e., the distance required for the steam to be absorbed into the airstream). This can vary from 18 in. to 5 ft and must be allowed for in the layout and dimensioning of the air-handling unit.

Dehumidifiers

For most routine applications, such as offices, residences, and schools, the air-handling unit's cooling coil provides adequate dehumidification. Where a specialty application requires additional moisture removal, desiccant dehumidifiers are an available accessory. Dust can be a problem with solid desiccants, and lithium contamination is a concern with spray equipment. Chapter 22 discusses dehumidification by cooling coils, and Chapter 23 discusses desiccant dehumidifiers.

Energy Recovery Devices

Energy recovery devices are in greater demand as outside air percentage increases. With some exceptions, ASHRAE *Standard* 90.1 requires energy recovery devices for air-handling units exceeding 5000 cfm and 70% or more outside air. They are used extensively in research and development facilities and in hospitals and laboratories with high outside air requirements. Many types are available, and the type of facility usually determines which is most suitable. Choices include heat pipes, runaround loops, fixed-plate energy exchangers, and rotary wheel energy exchangers. See Chapter 25 for detail.

Most manufacturers of commercial factory-packaged air-handling units now offer optional energy recovery modules for both small and large unit applications, which were formerly the domain of large custom air-handling units.

Many countries with extreme climates provide heat exchangers on outside/relief air, even for private homes. This trend is now appearing in both modest and large commercial buildings worldwide. Under certain circumstances, heat recovery devices can save energy and reduce the required capacity of primary cooling and heating plants by 20% or more.

Sound Control Devices

Where noise control is important, air-handling units can be specified with a noise control section, ranging from a plenum lined with acoustic duct liner to a full bank of duct silencers. This option is available in the smallest to largest units. Sound attenuation can be designed into the discharge (supply) end of the air-handling unit to reduce ductborne fan noise. Remember to consider ductborne noise traveling down the return or outside air paths in a noise-sensitive application, and use a sound attenuation module if necessary at the inlet end of an air-handling unit. See Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications* for detail.

Supply Air Fan

Axial-flow, centrifugal, or plenum (plug) fans may be chosen as supply air fans for straight-through flow applications. In factory-fabricated units, more than one centrifugal fan may be tied to the same shaft. If headroom permits, a single-inlet fan should be chosen when air enters at right angles to the flow of air through the equipment. This allows direct airflow from the fan wheel into the supply duct without abrupt change in direction and loss in efficiency. It also allows a more gradual transition from the fan to the duct and increases static regain in the velocity pressure conversion. To minimize inlet losses, the distance between casing walls and fan inlet should be at least the diameter of the fan wheel. With a single-inlet fan, the length of the transition section should be at least half the width or height of the casing, whichever is longer. If fans blow through the equipment, air distribution through the downstream components needs analyzing, and baffles should be used to ensure uniform air distribution. See Chapter 20 for more information.

Two placements of the supply fan section are common. A supply fan placed downstream of the cooling coil is known as a draw-through arrangement, because air is drawn, or induced, across the cooling coil. Similarly, a supply fan placed upstream of the cooling coil is called the blow-through position. Either arrangement is possible in both small and large air-handling units, and in factory-packaged and custom field-erected units.

A **draw-through system** (illustrated in Figure 1) draws air across the coils. A draw-through system usually provides a more even air distribution over all parts of the coil. However, some fan heat is added to the airstream after the air has crossed the cooling coil and must be taken into account when calculating the desired supply air temperature.

A **blow-through system** (illustrated in Figure 1) requires some caution on the part of the designer, because the blast effect of the supply fan outlet can concentrate a high percentage of the total air over a small percentage of the downstream coil surfaces. Air diffusers or diverters may be required. Consequently, blow-through air-handling units may tend to be longer overall than comparable draw-through units. This arrangement offers the advantage of placing the fan before the cooling coil, allowing the cooling coil to remove fan heat from the system. NFPA 54-2006, *National Fuel Gas Code*, requires the blow-through arrangement where natural-gas-fired heat exchangers are used for heating.

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Miscellaneous Components

Vibration and sound isolation equipment is required for many central fan installations. Standard mountings of fiberglass, ribbed rubber, neoprene mounts, and springs are available for most fans and prefabricated units. The designer must account for seismic restraint requirements for the seismic zone in which the project is located (see Chapter 54 of the 2007 *ASHRAE Handbook—HVAC Applications*). In some applications, fans may require concrete inertia blocks in addition to spring mountings. Steel springs require sound-absorbing material inserted between the springs and the foundation. Horizontal discharge fans operating at a high static pressure frequently require thrust arrestors. Ductwork connections to fans should be made with fireproof fiber cloth sleeves having considerable slack, but without offset between the fan outlet and rigid duct. Misalignment between the duct and fan outlet can cause turbulence, generate noise, and reduce system efficiency. Electrical and piping connections to vibration-isolated equipment should be made with flexible conduit and flexible connections.

Equipment noise transmitted through ductwork can be reduced by sound-absorbing units, acoustical lining, and other means of attenuation. Sound transmitted through the return and relief ducts should not be overlooked. Acoustical lining sufficient to adequately attenuate objectionable system noise or locally generated noise should be considered. Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications*, Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*, and ASHRAE *Standard* 68 have further information on sound and vibration control. Noise control, both in occupied spaces and outside near intake or relief louvers, must be considered. Some local ordinances may limit external noise produced by these devices.

AIR DISTRIBUTION

Once air-handling system and air-handling equipment have been selected, air must be distributed to the zone(s) served. Ductwork should deliver conditioned air to each zone as directly, quietly, and economically as possible. Air distribution ductwork and terminal devices selected must be compatible or the system will either fail to operate effectively or incur high first, operating, and maintenance costs.

Ductwork Design

Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals* describes ductwork design in detail and gives several methods of sizing duct systems, including static regain, equal friction, and T-method. Duct sizing is often performed manually for simple systems, but commercially available duct-sizing software programs are often used for larger and complex systems. It is imperative that the designer coordinate duct design with architectural and structural design. Structural features of the building generally require some compromise and often limit depth. In commercially developed projects, great effort is made to reduce floor-to-floor dimensions. In architecturally significant buildings, high ceilings, barrel-vault ceilings, rotundas and domes, ceiling coves, and other architectural details can place obstacles in the path of ductwork. The resultant decrease in available interstitial space left for ductwork can be a major design challenge. Layout of ductwork in these buildings requires experience, skill, and patience on the part of the designer.

Considerations. Duct systems can be designed for high or low velocity. A high-velocity system has smaller ducts, which save space but require higher pressures and may result in more noise. In some low-velocity systems, medium or high fan pressures may be required for balancing or to overcome high pressure drops from terminal devices. In any variable-flow system, changing operating conditions can cause airflow in the ducts to differ from design flow. Thus, varying airflow in the supply duct must be carefully analyzed to ensure that the system performs efficiently at all loads. This precaution is particularly needed with high-velocity air. Return air ducts are usually sized by the equal friction method.

In many applications, the space between a suspended ceiling and the floor slab or roof above it is used as a return air plenum, so that return air is collected at a central point. Governing codes should be consulted before using this approach in new design, because most codes prohibit combustible material in a ceiling space used as a return air plenum. For example, the *National Electrical Code® Handbook* (NFPA 2005) requires that either conduit or PTFE-insulated wire (often called plenum-rated cable) be installed in a return air plenum. In addition, regulations often require that return air plenums be divided into smaller areas by firewalls and that fire dampers be installed in ducts, which increases first cost.

In research and some industrial facilities, return ducting must be installed to avoid contamination and growth of biological contaminants in the ceiling space. Lobby ceilings with lay-in panels may not work well as return plenums where negative pressure from high-rise elevators or stack effects of high-rise buildings may occur. If the plenum leaks to the low-pressure area, the tiles may lift and drop out when the outside door is opened and closed. Return plenums directly below a roof deck have substantially greater return air temperature increases or decreases than a duct return.

Corridors should not be used for return air because they spread smoke and other contaminants. Although most codes ban returning air through corridors, the method is still used in many older facilities.

All ductwork should be sealed. Energy waste because of leaks in the ductwork and terminal devices can be considerable. Unsealed ductwork in many commercial buildings can have significant leakage.

Air systems are classified in two categories:

- **Single-duct systems** contain the main heating and cooling coils in a series-flow air path. A common duct distribution system at a common air temperature feeds all terminal apparatus. Capacity can be controlled by varying the air temperature or volume.
- **Dual-duct systems** contain the main heating and cooling coils in parallel-flow or series/parallel-flow air paths with either (1) a separate cold- and warm-air duct distribution system that blends air at the terminal apparatus (dual-duct systems), or (2) a separate supply air duct to each zone with the supply air blended at the main unit with mixing dampers (multizone). Dual-duct systems generally vary the supply air temperature by mixing two airstreams of different temperatures, but they can also vary the volume of supply air in some applications.

These categories are further divided and described in the following sections.

SINGLE-DUCT SYSTEMS

Constant Volume

While maintaining constant airflow, single-duct constant volume systems change the supply air temperature in response to the space load (Figure 9).

Single-Zone Systems. The simplest all-air system is a supply unit serving a single zone. The unit can be installed either in or remote from the space it serves, and may operate with or without distribution ductwork. Ideally, this system responds completely to the space needs, and well-designed control systems maintain temperature and humidity closely and efficiently. Single-zone systems often involve short ductwork with low pressure drop and thus low fan energy, and can be shut down when not required without affecting operation of adjacent areas, offering further energy savings. A return or relief fan may be needed, depending on system capacity and whether 100% outside air is used for cooling as part of an economizer cycle. Relief fans can be eliminated if overpressurization can be relieved by other means, such as gravity dampers.

Multiple-Zone Reheat Systems. Multiple-zone reheat is a modification of the single-zone system. It provides (1) zone or space control for areas of unequal loading, (2) simultaneous heating or cooling of perimeter areas with different exposures, and (3) close control for temperature, humidity, and space pressure in process or comfort applications. As the word *reheat* implies, heat is added as a secondary simultaneous process to either preconditioned (cooled, humidified, etc.) primary air or recirculated room air. Relatively small low-pressure systems place reheat coils in the ductwork at each zone. More complex designs include high-pressure primary distribution ducts to reduce their size and cost, and pressure reduction devices to maintain a constant volume for each reheat zone.

The system uses conditioned air from a central unit, generally at a fixed cold-air temperature that is low enough to meet the maximum cooling load. Thus, all supply air is always cooled the maximum amount, regardless of the current load. Heat is added to the airstream in each zone to avoid overcooling that zone, for every zone except the zone experiencing peak cooling demand. The result is very high energy use, and therefore use of this system is restricted by ASHRAE *Standard* 90.1. However, the supply air temperature from the unit can be varied, with proper control, to reduce the amount of reheat required and associated energy consumption. Care must be taken to avoid high internal humidity when the temperature of air leaving the cooling coil is allowed to rise during cooling.

In cold weather, when a reheat system heats a space with an exterior exposure, the reheat coil must not only replace the heat lost from the space, but also must offset the cooling of the supply air (enough cooling to meet the peak load for the space), further increasing energy consumption. If a constant-volume system is oversized, reheat cost becomes excessive.

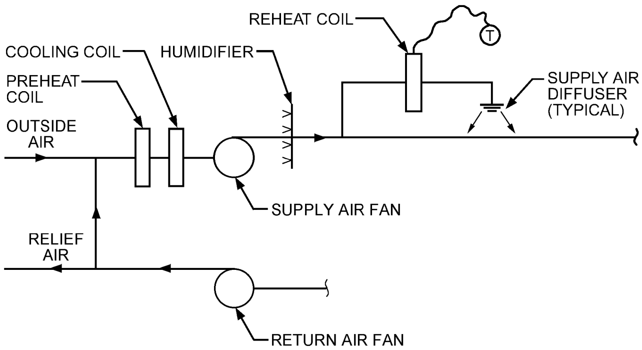

Fig. 9 Constant-Volume System with Reheat

In commercial applications, use of a constant-volume reheat system is generally discouraged in favor of variable-volume or other systems. Constant-volume reheat systems may continue to be applied in hospitals, laboratories, and other critical applications where variable airflow may be detrimental to proper pressure relationships (e.g., for infection control).

Variable Air Volume (VAV)

A VAV system (Figure 10) controls temperature in a space by varying the quantity of supply air rather than varying the supply air temperature. A VAV terminal unit at the zone varies the quantity of supply air to the space. The supply air temperature is held relatively constant. Although supply air temperature can be moderately reset depending on the season, it must always be low enough to meet the cooling load in the most demanding zone and to maintain appropriate humidity. VAV systems can be applied to interior or perimeter zones, with common or separate fans, with common or separate air temperature control, and with or without auxiliary heating devices. The greatest energy saving associated with VAV occurs at the perimeter zones, where variations in solar load and outside temperature allow the supply air quantity to be reduced.

Humidity control is a potential problem with VAV systems. If humidity is critical, as in certain laboratories, process work, etc., constant-volume airflow may be required.

Other measures may also maintain enough air circulation through the room to achieve acceptable humidity levels. The human body is more sensitive to elevated air temperatures when there is little air movement. Minimum air circulation can be maintained during reduced load by (1) raising the supply air temperature of the entire system, which increases space humidity, or supplying reheat on a zone-by-zone basis; (2) providing auxiliary heat in each room independent of the air system; (3) using individual-zone recirculation and blending varying amounts of supply and room air or supply and ceiling plenum air with fan-powered VAV terminal units, or, if design permits, at the air-handling unit; (4) recirculating air with a VAV induction unit; or (5) providing a dedicated recirculation fan to increase airflow.

VAV reheat can ensure close room space pressure control with the supply terminal functioning in sync with associated room exhaust. A typical application might be a fume hood VAV exhaust with constant open sash velocity (e.g., 85 or 100 fpm) or occupied/unoccupied room hood exhaust (e.g., 100 fpm at sash in occupied periods and 60 fpm in unoccupied periods).

Dual-Conduit. This method is an extension of the single-duct VAV system: one supply duct offsets exterior transmission cooling or heating loads by its terminal unit with or without auxiliary heat, and the other supply air path provides cooling throughout the year. The

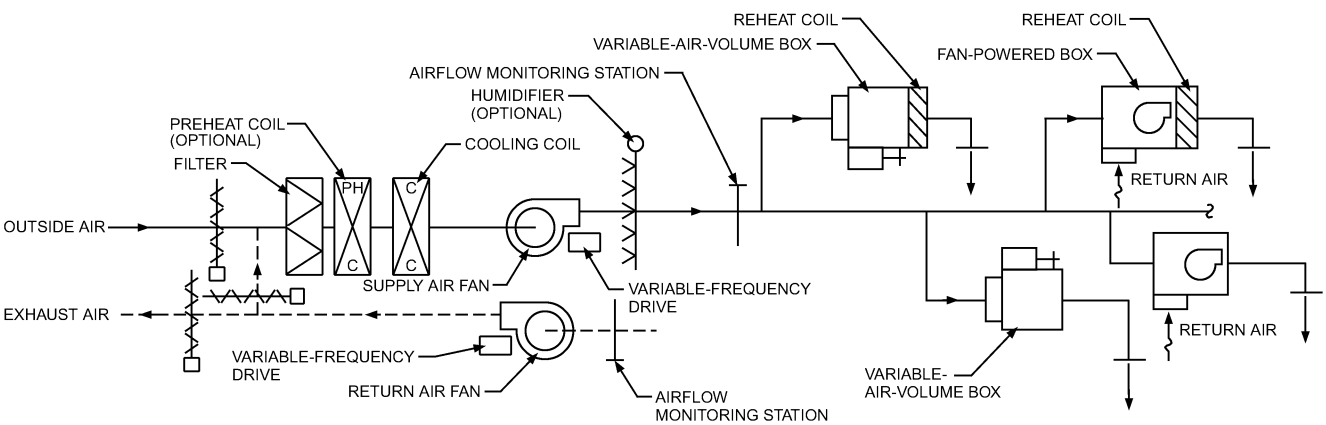

Fig. 10 Variable-Air-Volume System with Reheat and Induction and Fan-Powered Devices
(Courtesy RDK Engineers)

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first airstream (primary air) operates as a constant-volume system, and the air temperature is varied to offset transmission only (i.e., it is warm in winter and cool in summer). Often, however, the primary-air fan is limited to operating only during peak heating and cooling periods to further reduce energy use. When calculating this system's heating requirements, the cooling effect of secondary air must be included, even though the secondary system operates at minimum flow. The other airstream, or secondary air, is cool year-round and varies in volume to match the load from solar heating, lights, power, and occupants. It serves both perimeter and interior spaces.

Variable Diffuser. The discharge aperture of this diffuser is reduced to keep discharge velocity relatively constant while reducing conditioned supply airflow. Under these conditions, the induction effect of the diffuser is kept high, cold air mixes in the space, and the room air distribution pattern is more nearly maintained at reduced loads. These devices are of two basic types: one has a flexible bladder that expands to reduce the aperture, and the other has a diffuser plate that moves. Both devices are pressure-dependent, which must be considered in duct-distribution system design. They are either powered by the system or pneumatically or electrically driven.

DUAL-DUCT SYSTEMS

A dual-duct system conditions all the air in a central apparatus and distributes it to conditioned spaces through two ducts, one carrying cold air and the other carrying warm air. In each conditioned zone, air valve terminals mix warm and cold air in proper proportion to satisfy the space temperature and pressure control. Dual-duct systems may be designed as constant volume or variable air volume; a dual-duct, constant-volume system uses more energy than a single-duct VAV system. As with other VAV systems, certain primary-air configurations can cause high relative humidity in the space during the cooling season.

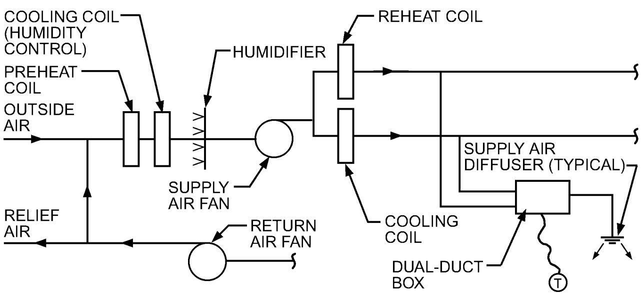

Fig. 11 Single-Fan, Dual-Duct System

Constant Volume

Dual-duct, constant-volume systems using a single supply fan were common through the mid-1980s, and were used frequently as an alternative to constant-volume reheat systems. Today, dual-fan, dual-duct are preferred over the former, based on energy performance. There are two types of dual-duct, single-fan application: with reheat, and without.

Single Fan With Reheat. There are two major differences between this and a conventional terminal reheat system: (1) reheat is applied at a central point in the fan unit hot deck instead of at individual zones (Figure 11), and (2) only part of the supply air is cooled by the cooling coil (except at peak cooling demand); the rest of the supply is heated by the hot-deck coil during most hours of operation. This uses less heating and cooling energy than the terminal reheat system where all the air is cooled to full cooling capacity for more operating hours, and then all of it is reheated as required to match the space load. Fan energy is constant because airflow is constant.

Single Fan Without Reheat. This system has no heating coil in the fan unit hot deck and simply pushes a mixture of outside and recirculated air through the hot deck. A problem occurs during periods of high outside humidity and low internal heat load, causing the space humidity to rise rapidly unless reheat is added. This system has limited use in most modern buildings because most occupants demand more consistent temperature and humidity. A single-fan, no-reheat dual-duct system does not use any extra energy for reheat, but fan energy is constant regardless of space load.

Variable Air Volume

Dual-duct VAV systems blend cold and warm air in various volume combinations. These systems may include single-duct VAV terminal units connected to the cold-air duct distribution system for cooling only interior spaces (see Figures 11 and 12), and the cold duct may serve perimeter spaces in sync with the hot duct. This saves reheat energy for the air for those cooling-only zones because space temperature control is by varying volume, not supply air temperature, which may save some fan energy to the extent that the airflow matches the load.

Newer dual-duct air terminals provide two damper operators per air terminal, which allows the unit to function like a single-duct VAV cooling terminal unit (e.g., 10 in. inlet damper) and a single-duct VAV heating terminal unit (e.g., 6 in. inlet damper) in one physical terminal package. This arrangement allows the designer to

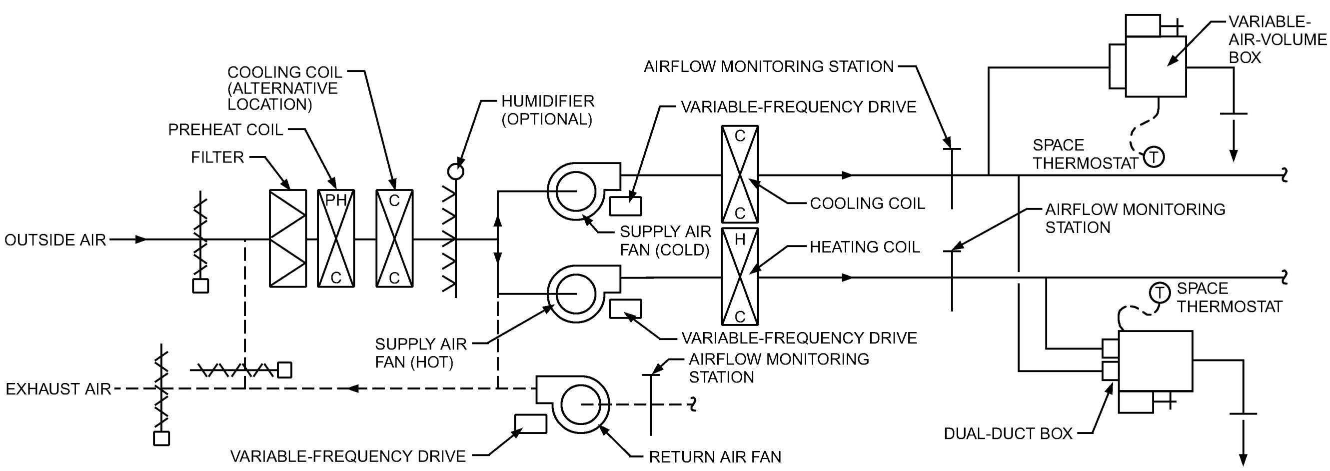

Fig. 12 Dual-Fan, Dual-Duct System
(Courtesy RDK Engineers)

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specify the correct cold-air supply damper as part of the dual-duct terminal, which is usually a large supply air quantity in sync with a smaller hot-air supply damper in the same terminal unit. This use of significant minimum airflow levels, providing temperature control by means of dual-duct box mixing at minimum airflow. This variation saves both heating and cooling energy and fan energy because the terminal damper sizes are more appropriate for the design flow versus antiquated dual-duct terminals that provided same-size cold and hot dampers and a single damper operator that did not allow space temperature and airflow controllability.

Single-Fan, Dual-Duct System. This system (Figure 11), frequently used as a retrofit to an antiquated dual-duct, single-fan application during the 1980s and 1990s, uses a single supply fan sized for the peak cooling load or the coincident peak of the hot and cold decks. Fan control is from two static-pressure controllers, one located in the hot deck and the other in the cold deck. The duct requiring the highest pressure governs the airflow by signaling the supply fan VFD speed control. An alternative is to add discharge supply air duct damper control to both the cold and hot ducts to vary flow while the supply fan operates up and down its fan curve. Return air fan tracking of discharge supply air must be assessed with this application.

Usually, the cold deck is maintained at a fixed temperature, although some central systems allow the temperature to rise during warmer weather to save refrigeration. The hot-deck temperature is often raised during periods of low outside temperature and high humidity to increase the flow over the cold deck for dehumidification. Other systems, particularly in laboratories, use a precooling coil to dehumidify the total airstream or just the outside air to limit humidity in the space. Return air quantity can be controlled either by flow-measuring devices in the supply and return duct or by static-pressure controls that maintain space static pressure.

Dual-Fan, Dual-Duct System. Supply air volume of each supply fan is controlled independently by the static pressure in its respective duct (Figure 12). The return fan is controlled based on the sum of the hot and cold fan volumes using flow-measuring stations. Each fan is sized for the anticipated maximum coincident hot or cold volume, not the sum of the instantaneous peaks. The cold deck can be maintained at a constant temperature either with mechanical refrigeration, when minimum outside air is required, or with an air-side economizer, when outside air is below the temperature of the cold-deck set point. This operation does not affect the hot deck, which can recover heat from the return air, and the heating coil need operate only when heating requirements cannot be met using return air. Outside air can provide ventilation air via the hot duct when the outside air is warmer than the return air. However, controls should be used to prohibit introducing excessive amounts of outside air beyond the required minimum when that air is more humid than the return air.

MULTIZONE SYSTEMS

The multizone system (Figure 13) supplies several zones from a single, centrally located air-handling unit. Different zone requirements are met by mixing cold and warm air through zone dampers at the air handler in response to zone thermostats. The mixed, conditioned air is distributed throughout the building by single-zone ducts. The return air is handled conventionally. The multizone system is similar to the dual-duct system and has the same potential problem with high humidity levels. This system can provide a smaller building with the advantages of a dual-duct system, and it uses packaged equipment, which is less expensive.

Packaged equipment is usually limited to about 12 zones, although built-up systems can include as many zones as can be physically incorporated in the layout. A multizone system is somewhat more energy-efficient than a terminal reheat system because not all the air goes through the cooling coil, which reduces the amount of reheat required. But a multizone system uses essentially the same fan energy as terminal reheat because the airflow is constant.

Two common variations on the multizone system are the three-deck multizone and the Texas multizone. A **three-deck multizone** system is similar to the standard multizone system, but bypass zone dampers are installed in the air-handling unit parallel with the hot- and cold-deck dampers. In the **Texas multizone** system, the hot-deck heating coil is removed from the air handler and replaced with an air-resistance plate matching the cooling coil's pressure drop. Individual heating coils are placed in each perimeter zone duct. These heating coils are usually located in the equipment room for ease of maintenance. This system is common in humid climates where the cold deck often produces 48 to 52°F air for humidity control. Using the air-handling units' zone dampers to maintain zone conditions, supply air is then mixed with bypass air rather than heated air. Heat is added only if the zone served cannot be maintained by delivering return air alone. These arrangements can save considerable reheat energy.

SPECIAL SYSTEMS

Primary/Secondary

Some processes use two interconnected all-air systems (Figure 14). In these situations, space gains are very high and/or a large number of air changes are required (e.g., in sterile or cleanrooms or where close-tolerance conditions are needed for process work). The primary system supplies the conditioned outside air requirements for the process to the secondary system. The secondary system provides additional cooling and humidification (and heating, if required) to offset space and fan power gains. Normally, the secondary cooling coil is designed to be dry (i.e., sensible cooling only) to reduce the possibility of bacterial growth, which can create air quality problems. The alternative is to have the primary system supply conditioned outside air [e.g., 20 air changes per hour (ach)] to the ceiling return air plenum, where fan-powered HEPA filter units provide the total supply air (e.g., 120 ach) to the occupied space. Consideration must be given to the total heat gain from the numerous fan-powered motors in the return air plenum.

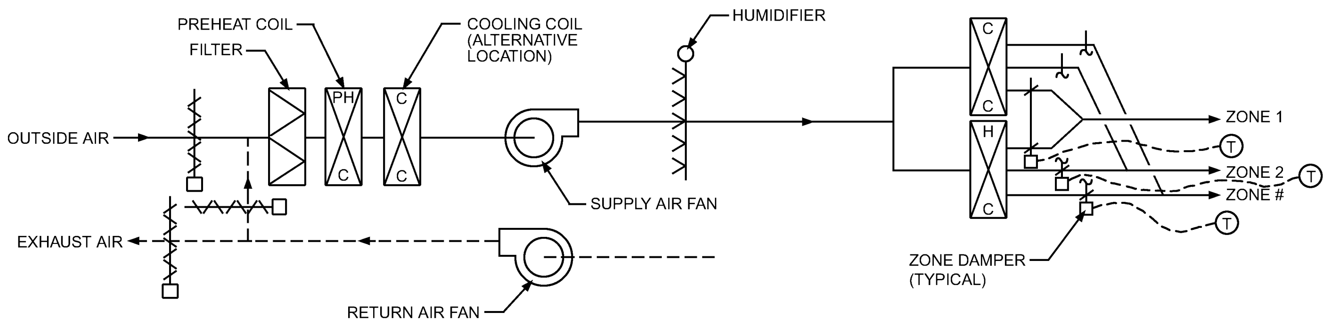

Fig. 13 Multizone System
(Courtesy RDK Engineers)

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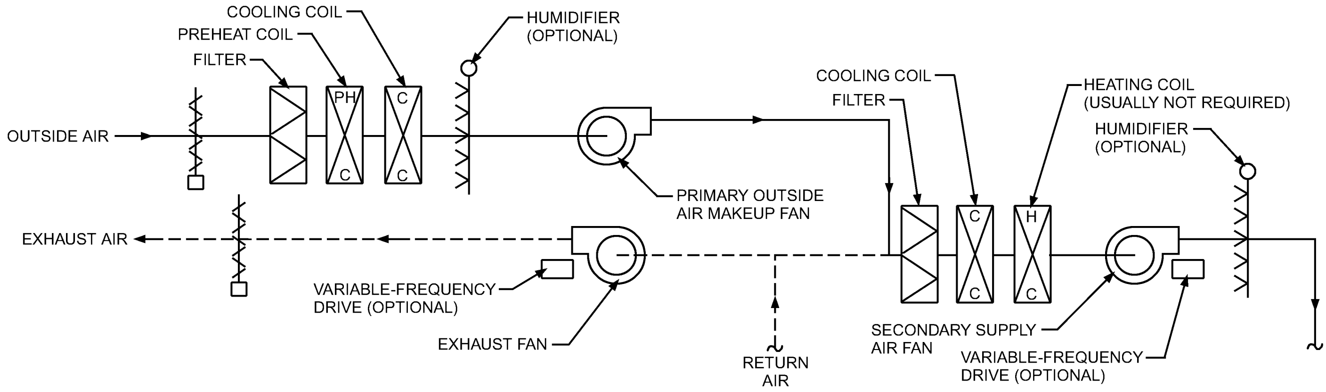

Fig. 14 Primary/Secondary System
(Courtesy RDK Engineers)

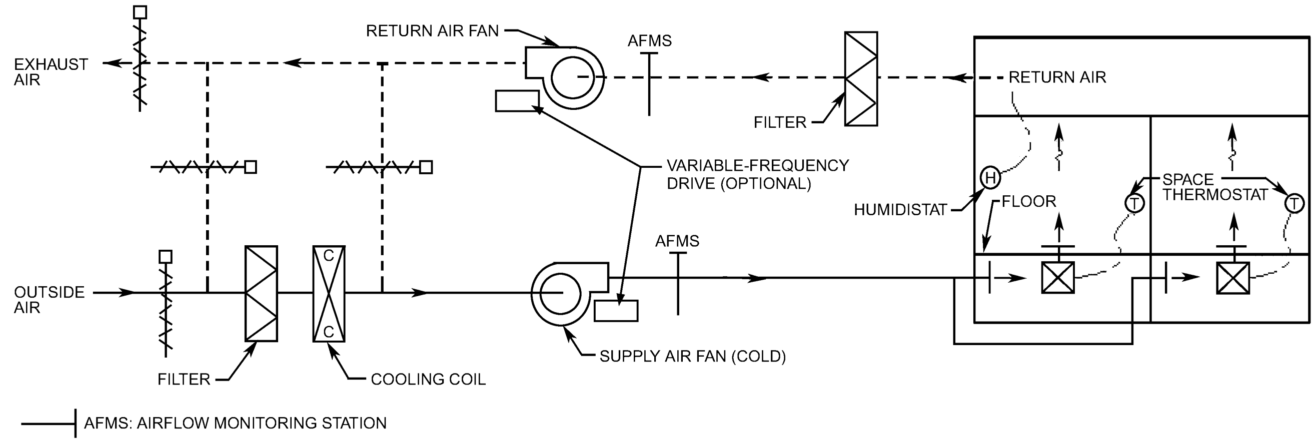

Fig. 15 Underfloor Air Distribution
(Courtesy RDK Engineers)

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Dedicated Outdoor Air

Similar in some respects to the primary/secondary system, the dedicated outdoor air system (DOAS) decouples air-conditioning of the outside air from conditioning of the internal loads. Long popular in hotels and multifamily residential buildings, DOAS is now gaining popularity in commercial buildings and many other applications. The DOAS introduces 100% outside air, heats or cools it, may humidify or dehumidify it, and filters it, then supplies this treated air to each of its assigned spaces. Air volume is sized in response to minimum ventilation standards, such as ASHRAE *Standard* 62.1, or to meet makeup air demands. Often, the DOAS serves multiple spaces and is designed not necessarily to control space temperature, but to provide thermally neutral air to those spaces. A second, more conventional system serves those same spaces and is intended to control space temperature. The conventional system is responsible for offsetting building envelope and internal loads. In this instance, however, the conventional system has no responsibility for conditioning or delivering outside air. A common example may be a large apartment building with individual fan-coil units (the conventional system) in each dwelling unit, plus a common building-wide DOAS to deliver code-required outside air to each housing unit for good indoor air quality and to make up bathroom and/or kitchen exhaust. Another application is to provide minimum outside air ventilation while space temperature control is achieved with radiant panels, chilled beams, valance heating and cooling, etc.

Underfloor Air Distribution

An underfloor air distribution (UFAD) system (Figure 15) uses the open space between a structural floor slab and the underside of a raised-floor system to deliver conditioned air to supply outlets at or near floor level. Floor diffusers make up the large majority of installed UFAD supply outlets, which can provide different levels of individual control over the local thermal environment, depending on diffuser design and location. UFAD systems use the same basic types of equipment at the cooling and heating plants and primary air-handling units as conventional overhead systems do. Variations of UFAD include displacement ventilation and task/ambient systems.

Displacement ventilation is a type of UFAD system that uses a large number of low-volume supply air outlets to create laminar flow. Conditioned air slightly cooler than the desired room air temperature in the occupied zone is supplied from air outlets at low air velocities (~100 fpm or less). Because of buoyancy, the cooler air spreads along the floor and floods the room's lower zone. Typically, outlets are located at or near the floor, and supply air is introduced directly into the occupied zone. Exhaust or air returns are located at or close to the ceiling or roof. Further information on displacement air distribution systems can be found in Goodfellow and Tahti (2001).

A **task/ambient conditioning (TAC)** system is defined as any space-conditioning system that allows thermal conditions in small, localized zones (e.g., regularly occupied work locations) to be individually controlled by nearby building occupants while automatically maintaining acceptable environmental conditions in the ambient space of the building (e.g., corridors, open-use space, other areas outside of regularly occupied work space). Typically, the occupant can control the perceived temperature of the local environment by adjusting the speed and direction, and in some cases the temperature, of incoming air supply, much like on the dashboard of a car. TAC systems are distinguished from standard

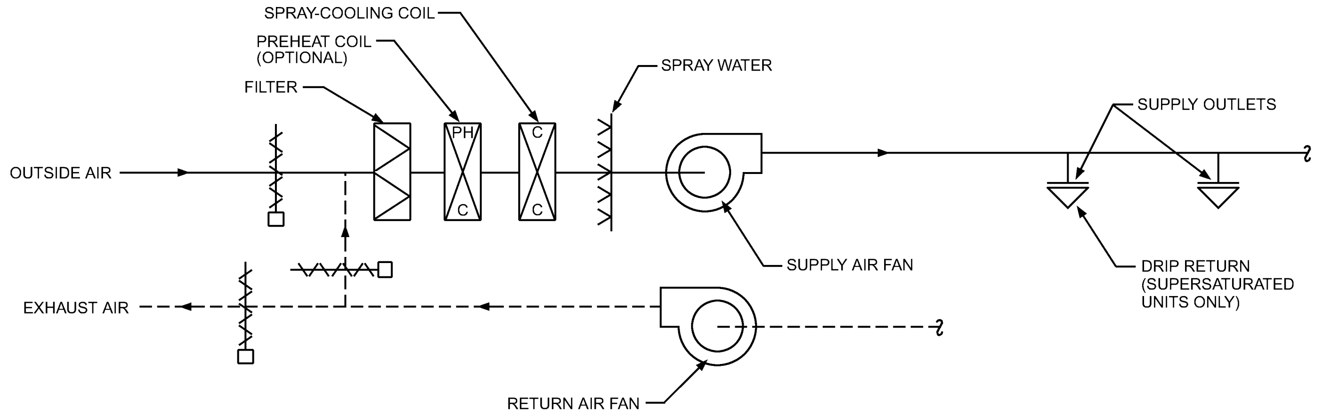

Fig. 16 Supersaturated/Wetted Coil
(Courtesy RDK Engineers)

UFAD systems by the higher degree of personal comfort control provided by the localized supply outlets. TAC supply outlets use direct-velocity cooling to achieve this level of control, and are therefore most commonly configured as fan-driven (active) jet-type diffusers that are part of the furniture or partitions. Active floor diffusers are also possible.

Unlike conventional HVAC design, in which conditioned air is both supplied and exhausted at ceiling level, UFAD removes supply ducts from the ceilings and allows a smaller overhead ceiling cavity. Less stratification and improved ventilation effectiveness may be achieved with UFAD because air flows from a floor outlet to a ceiling inlet, rather than from a ceiling outlet to a ceiling inlet. UFAD has long been popular in computer room and data center applications, and in Europe in conventional office buildings. It is now increasingly applied in North American offices and other commercial buildings.

Because raised floors contain electrical conduits, floor drains, wall partitions, and other items, installed by many trades, underfloor plenums require careful pressure-testing for leakage.

For more information, see Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals*, Chapters 17 and 29 of the 2007 *ASHRAE Handbook—HVAC Applications*, or Bauman (2003).

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Wetted Duct/Supersaturated

Some industries spray water into the airstream at central air-handling units in sufficient quantities to create a controlled carry-over (Figure 16). This supercools the supply air, normally equivalent to an oversaturation of about 10 grains per pound of air, and allows less air to be distributed for a given space load. These are used where high humidity is desirable, such as in the textile or tobacco industry, and in climates where adiabatic cooling is sufficient.

Compressed-Air and Water Spray

This is similar to the wetted duct system, except that the water is atomized with compressed air and provides limited cooling while maintaining a relatively humid environment. Nozzles are sometimes placed inside the conditioned space and independent of the cooling air supply, and can be used for large, open manufacturing facilities where humidity is needed to avoid static electricity in the space. Several nozzle types are available, and the designer should understand their advantages and disadvantages. Depending on the type of nozzle, compressed-air and water spray systems can require large and expensive air compressors. The extra first cost may or may not be offset by energy cost savings, depending on the application.

Low-Temperature

Ice storage is often used to reduce peak electrical demand. Low-temperature systems (where air is supplied at as low as 40°F) are sometimes used. Benefits include smaller central air-handling units and associated fan power, and smaller supply air duct distribution. At air terminals, fan-powered units are frequently used to increase supply air to the occupied space. Attention to detail is important because of the low air temperature and the potential for excessive condensate on supply air duct distribution in the return plenum space. These fan-powered terminals mix return air or room air with cold supply air to increase the air circulation rate in the space.

Smoke Management

Air-conditioning systems are often used for smoke control during fires. Controlled airflow can provide smoke-free areas for occupant evacuation and fire fighter access. Space pressurization creates a low-pressure area at the smoke source, surrounding it with high-pressure spaces. The air-conditioning system can also be designed to provide makeup air for smoke exhaust systems in atria and other large spaces (Duda 2004). For more information, see Chapter 52 of the 2007 *ASHRAE Handbook—HVAC Applications*. Klote and Milke (2002) also has detailed information on this topic.

TERMINAL UNITS

Air systems have two types of devices between the primary air distribution system and the conditioned space: (1) passive devices, such as supply outlets (registers or diffusers) and return inlets (grilles), and (2) active devices, which are often called *terminal units.* The register or diffuser should deliver supply air throughout the conditioned space without occupants sensing a draft and without creating excessive noise. The terminal unit controls the quantity and/or temperature of the supply air to maintain desired conditions in the space. Both types of devices are discussed in Chapter 19 of this volume and Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals*. Terminal units are discussed here briefly in terms of how they fit into the system concept, but Chapter 19 should be consulted for more complete information.

In some instances, such as in low-velocity all-air systems, air may enter from the supply air ductwork directly into the conditioned space through a grille or diffuser. In medium- and high-velocity air systems, air terminal units normally control air volume, reduce duct pressure, or both. Various types are available. A VAV terminal varies the amount of air delivered. Air may be delivered to low-pressure ductwork and then to the space, or the terminal may contain an integral air diffuser. A fan-powered VAV terminal varies the amount of primary air delivered, but it also uses a fan to mix ceiling plenum or return air with primary supply air before it is delivered to the space. An all-air induction terminal controls the volume of primary air, induces a flow of ceiling plenum or space air, and distributes the mixture through low-velocity ductwork to the space. An air-water induction terminal includes a coil or coils in the induced airstream to condition the return air before it mixes with the primary air and enters the space.

Constant-Volume Reheat

Constant-volume reheat terminal boxes are used mainly in terminal reheat systems with medium- to high-velocity ductwork. The unit serves as a pressure-reducing valve and constant-volume regulator to maintain a constant supply air quantity to the space, and is generally fitted with an integral reheat coil that controls space temperature. The constant supply air quantity is selected to provide cooling to match the peak load in the space, and the reheat coil is controlled to raise the supply air temperature as necessary to maintain the desired space temperature at reduced loads.

Variable Air Volume

VAV terminal units are available in many configurations, all of which control the space temperature by varying the volume of cool supply air from the air handler to match the actual cooling load. VAV terminal units are fitted with automatic controls that are either pressure-dependent or pressure-independent. **Pressure-dependent** units control damper position in response to room temperature, and flow may increase and decrease as the main duct pressure varies. **Pressure-independent** units measure actual supply airflow and control flow in response to room temperature. Pressure-independent units may sometimes be fitted with a velocity-limit control that overrides the room temperature signal to limit the measured supply velocity to some selected maximum. Velocity-limit control can be used to prevent excess airflow through units nearest the air handler. Excessive airflow at units close to the air handler can draw so much supply air that units far from the air handler do not get enough air.

Throttling Without Reheat. The throttling (or pinch-off) box without reheat is essentially an air valve or damper that reduces supply airflow to the space in response to falling space temperature. The unit usually includes some means of sound attenuation to reduce air noise created by the throttling action. It is the simplest and least expensive VAV terminal unit, but is suitable for use only where no heat is required and if the unit can go to the completely closed position at reduced cooling loads. If this type of unit is set up with a minimum position, it will constantly provide cooling to the space, whether the space needs it or not, and can overcool the space. This approach offers the lowest fan energy use, because it minimizes airflow to just the amount required by the cooling load.

Throttling With Reheat. This simple VAV system integrates heating at the terminal unit with the same type of air valve. It is applied in interior and exterior zones where full heating and cooling flexibility is required. These terminal units can be set to maintain a predetermined minimum air quantity necessary to (1) offset the heating load, (2) limit maximum humidity, (3) provide reasonable air movement in the space, and (4) provide required ventilation air. The reheat coil is most commonly hot water or electric resistance.

Variable air volume with reheat allows airflow to be reduced as the first step in control; heat is then initiated as the second step. Compared to constant-volume reheat, this procedure reduces operating cost appreciably because the amount of primary air to be cooled and secondary air to be heated is reduced. Many types of controls can provide control sequences with more than one minimum airflow. This type of control allows the box to go to a lower flow rate that just meets ventilation requirements at the lightest cooling loads, then increase to a higher flow rate when the heating coil is energized. A feature can be provided to isolate the availability of reheat during the summer, except in situations where even low airflow would overcool the space and should be avoided or where increased humidity causes discomfort (e.g., in conference rooms when the lights are turned off).

Because the reheat coil requires some minimum airflow to deliver heat to the space, and because the reheat coil must absorb all of the cooling capacity of that minimum airflow before it starts to deliver heat to the space, energy use can be significantly higher than with throttling boxes that go fully closed.

Dual-Duct. Dual-duct systems typically feature throttling dual-duct VAV boxes. These terminal units are very similar to the single-duct VAV boxes discussed above, but as the name implies, two primary air inlets are provided. This allows connection of one primary air inlet to a heating duct and the other to a cooling duct. The dual-duct box then modulates both air dampers in response to instructions from a thermostat. Dual-duct boxes are generally available in a constant-volume output, with cooling and heating dampers operating in tandem but inversely such that the sum total of heating plus cooling is always relatively constant. Dual-duct boxes are also available in a variable-volume output, with only the cooling or heating damper permitted to stroke open at any given time, such that cooling damper must be closed prior to allowing the heating damper to stroke open. Minimum positions are available on these dampers to meet minimum ventilation airflow requirements even when little or no airflow would otherwise be required.

Induction. The VAV induction system uses a terminal unit to reduce cooling capacity by simultaneously reducing primary air and inducing room or ceiling air (replacing the reheat coil) to maintain a relatively constant room supply volume. This operation is the reverse of the bypass box. The primary-air quantity decreases with load, retaining the savings of VAV, and the air supplied to the space is kept relatively constant to avoid the effect of stagnant air or low air movement. VAV induction units require a higher inlet static pressure, which requires more fan energy, to achieve the velocities necessary for induction. Today, induction units have for the most part been displaced by fan-powered terminals, which allow reduction of inlet static pressure and, in turn, reduced central air-handling unit fan power.

Fan-Powered. Fan-powered systems are available in either parallel or series airflow. In **parallel-flow** units, the fan is located outside the primary airstream to allow intermittent fan operation. A backdraft damper on the terminal fan prevents conditioned air from escaping into the return air plenum when the terminal fan is off. In **series** units, the fan is located in the primary airstream and runs continuously when the zone is occupied. These constant-airflow fan boxes in a common return plenum can help maintain indoor air quality by recirculating air from overventilated zones to zones with greater outside air ventilation requirements.

Fan-powered systems, both series and parallel, are often selected because they maintain higher air circulation through a room at low loads but still retain the advantages of VAV systems. As the cold primary-air valve modulates from maximum to minimum (or closed), the unit recirculates more plenum air. In a perimeter zone, a hot-water heating coil, electric heater, baseboard heater, or remote radiant heater can be sequenced with the primary-air valve to offset external heat losses. Between heating and cooling operations, the fan only recirculates ceiling air. This allows heat from lights to be used for space heating, for maximum energy saving. During unoccupied periods, the main supply air-handling unit remains off and individual fan-powered heating zone terminals are cycled to maintain required space temperature, thereby reducing operating cost during unoccupied hours.

Fans for fan-powered air-handling units operated in series are sized and operated to maintain minimum static pressures at the unit inlet connections. This reduces the fan energy for the central air handler, but the small fans in fan-powered units are less efficient than the large air handler fans. As a result, the series fan-powered unit (where small fans operate continuously) may use more fan energy than a throttling unit system. However, the extra fan energy may be more than offset by the reduction in reheat through the recovery of plenum heat and the ability to operate a small fan to deliver heat during unoccupied hours where heat is needed.

Because fan-powered boxes involve an operating fan, they may generate higher sound levels than throttling boxes. Acoustical

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ceilings generally are not very effective sound barriers, so extra care should be taken in considering the sound level in critical spaces near fan-powered terminal units.

Both parallel and series fan-powered terminal units should be provided with filters. A disadvantage of this type of terminal unit is the need to periodically change these filters, making them unsuitable for installation above inaccessible ceilings. A large building could contain hundreds of fan-powered terminal units, some of which might be located in inconvenient locations above office furniture or executive offices. Select installed locations carefully for maximum accessibility.

The constant (series) fan VAV terminal can accommodate minimum (down to zero) flow at the primary-air inlet while maintaining constant airflow to the space.

Both types of fan-powered units and induction terminal units are usually located in the ceiling plenum to recover heat from lights. This sometimes allows these terminals to be used without reheat coils in internal spaces. Perimeter-zone units are sometimes located above the ceiling of an interior zone where heat from the lights maintains a higher plenum temperature. Provisions must still be made for morning warm-up and night heating. Also, interior spaces with a roof load must have heat supplied either separately in the ceiling or at the terminal.

Terminal Humidifiers

Most projects requiring humidification use steam. This can be centrally generated as part of the heating plant, where potential contamination from water treatment of the steam is more easily handled and therefore of less concern. Where there is a concern, local generators (e.g., electric or gas) that use treated water are used. Compressed-air and water humidifiers are used to some extent, and supersaturated systems are used exclusively for special circumstances, such as industrial processes. Spray-type washers and wetted coils are also more common in industrial facilities. When using water directly, particularly in recirculating systems, the water must be treated to avoid dust accumulation during evaporation and the build-up of bacterial contamination.

Terminal Filters

In addition to air-handling unit filters, terminal filters may used at the supply outlets to protect particular conditioned spaces where an extra-clean environment is desired (e.g., in a hospital's surgery suite). Chapter 28 discusses this topic in detail.

AIR DISTRIBUTION SYSTEM CONTROLS

Controls should be automatic and simple for best operating and maintenance efficiency. Operations should follow a natural sequence. Depending on the space need, one controlling thermostat closes a normally open heating valve, opens the outside air mixing dampers, or opens the cooling valve. In certain applications, an enthalpy controller, which compares the heat content of outside air to that of return air, may override the temperature controller. This control opens the outside air damper when conditions reduce the refrigeration load. On smaller systems, a dry-bulb control saves the cost of the enthalpy control and approaches these savings when an optimum changeover temperature, above the design dew point, is established. Controls are discussed in more detail in Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Air-handling systems, especially variable-air-volume systems, should include means to measure and control the amount of outside air being brought in to ensure adequate ventilation for acceptable indoor air quality. Strategies include the following:

- Separate constant-volume 100% outside air ventilation systems
- Outside air injection fan
- Directly measuring the outside air flow rate
- Modulating the return damper to maintain a constant pressure drop across a fixed outside air orifice
- Airflow-measuring systems that measure both supply and return air volumes and maintain a constant difference between them.
- CO_2- and/or VOC-based demand-controlled ventilation

A minimum outside air damper with separate motor, selected for a velocity of 1500 fpm, is preferred to one large outside air damper with minimum stops. A separate damper simplifies air balancing. Proper selection of outside, relief, and return air dampers is critical for efficient operation. Most dampers are grossly oversized and are, in effect, unable to control. One way to solve this problem is to provide maximum and minimum dampers. A high velocity across a wide-open damper is essential to its providing effective control.

A mixed-air temperature control can reduce operating costs and also reduce temperature swings from load variations in the conditioned space. Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* shows control diagrams for various arrangements of central system equipment. Direct digital control (DDC) is common, and most manufacturers offer either a standard or optional DDC package for equipment, including air-handling units, terminal units, etc. These controls offer considerable flexibility. DDC controls offer the additional advantage of the ability to record actual energy consumption or other operating parameters of various components of the system, which can be useful for optimizing control strategies.

Constant-Volume Reheat. This system typically uses two subsystems for control: one controls the discharge air conditions from the air-handling unit, and the other maintains the space conditions by controlling the reheat coil.

Variable Air Volume. Air volume can be controlled by duct-mounted terminal units serving multiple air outlets in a control zone or by units integral to each supply air outlet.

Pressure-independent volume-regulator units control flow in response to the thermostat's call for heating or cooling. The required flow is maintained regardless of fluctuation of the VAV unit inlet or system pressure. These units can be field- or factory-adjusted for maximum and minimum (or shutoff) air settings. They operate at inlet static pressures as low as 0.2 in. of water.

Pressure-dependent devices control air volume in response to a unit thermostatic (or relative humidity) device, but flow varies with the inlet pressure variation. Generally, airflow oscillates when pressure varies. These units do not regulate flow but position the volume-regulating device in response to the thermostat. They are the least expensive units but should only be used where there is no need for maximum or minimum limit control and when the pressure is stable.

The type of controls available for VAV units varies with the terminal device. Most use either pneumatic or electric controls and may be either self-powered or system-air-actuated. Self-powered controls position the regulator by using liquid- or wax-filled power elements. System-powered devices use air from the air supplied to the space to power the operator. Components for both control and regulation are usually contained in the terminal device.

To conserve power and limit noise, especially in larger systems, fan operating characteristics and system static pressure should be controlled. Many methods are available, including fan speed control, variable-inlet vane control, fan bypass, fan discharge damper, and variable-pitch fan control. The location of pressure-sensing devices depends, to some extent, on the type of VAV terminal unit used. Where pressure-dependent units without controllers are used, the system pressure sensor should be near the static pressure midpoint of the duct run to ensure minimum pressure variation in the system. Where pressure-independent units are installed, pressure controllers may be at the end of the duct run with the highest static pressure loss. This sensing point ensures maximum fan power savings while maintaining the minimum required pressure at the last terminal.

As flow through the various parts of a large system varies, so does static pressure. Some field adjustment is usually required to find the

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best location for the pressure sensor. In many systems, the initial location is two-thirds to three-fourths of the distance from the supply fan to the end of the main trunk duct. As the pressure at the system control point increases as terminal units close, the pressure controller signals the fan controller to position the fan volume control, which reduces flow and maintains constant pressure. Many systems measure flow rather than pressure and, with the development of economical DDC, each terminal unit (if necessary) can be monitored and the supply and return air fans modulated to exactly match the demand.

Dual Duct. Because dual-duct systems are generally more costly to install than single-duct systems, their use is less widespread. DDC, with its ability to maintain set points and flow accurately, can make dual-duct systems worthwhile for certain applications. They should be seriously considered as alternatives to single-duct systems.

Personnel. The skill levels of personnel operating and maintaining the air conditioning and controls should be considered. In large research and development or industrial complexes, experienced personnel are available for maintenance. On small and sometimes even large commercial installations, however, office managers are often responsible, so designs must be in accordance with their capabilities.

Water System Interface. On large hydronic installations where direct blending is used to maintain (or reset) the secondary-water temperature, the system valves and coils must be accurately sized for proper control. Many designers use variable flow for hydronic as well as air systems, so the design must be compatible with the air system to avoid operating problems.

Relief Fans. In many applications, relief or exhaust fans can be started in response to a signal from the economizer control or to a space pressure controller. The main supply fan must be able to handle the return air pressure drop when the relief fan is not running.

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AUTOMATIC CONTROLS AND BUILDING MANAGEMENT SYSTEM

Central air-handling units increasingly come with prepackaged and prewired automatic control systems. Controls may also be accessible by the building manager using a modem to an off-site computer. The next level of HVAC system management is to integrate manufacturers' control packages with the building management system (BMS). If the project is an addition or major renovation of space, prepackaged controls and their capabilities need to be compatible with existing automatic controls. Chapter 39 of the 2007 *ASHRAE Handbook—HVAC Applications* discusses computer applications, and ASHRAE *Standard* 135 discusses interfacing building automation systems.

Automatic temperature controls can be important in establishing a simple or complex control system, more so with all-air systems than with air-and-water and all-water systems. Maintaining these controls can be challenging to building management staff. With a focus on energy management and indoor air quality, the building management system can be an important business tool in achieving sustainable facility management success.

MAINTENANCE MANAGEMENT SYSTEM

Maintenance management for central air-handling units involves many component and devices, with a varied lists of tasks (e.g., check belts, lube fittings, replace filters, adjust dampers), and varied times and frequencies, depending on components and devices (e.g., check damper linkage monthly, change filters based on pressure drop) Small installations may be best served by local service contractors, in lieu of in-house personnel; larger installations may be best served with in-house technicians. See Chapter 38 of the 2007 *ASHRAE Handbook—HVAC Applications* for further discussion.

BUILDING SYSTEM COMMISSIONING

Prepackaged control systems 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, the process can be more cumbersome because both control contractors need to participate. Air and water balancing for each all-air system are also important. With the complexity of the air systems and the numerous modes of operation (e.g., economizer cycle, minimum outside air, smoke control mode), it is essential to adjust and balance systems before system commissioning.

Ongoing commissioning or recommissioning should be integral to maintaining each central air system. During the warranty phase, all-air system performance should be measured and benchmarked to ensure continuous system success. Retro- or recommissioning should be considered whenever the facility is expanded or an additional connection made to the existing systems, to ensure the original design intent is met.

When completing TAB and commissioning, consider posting laminated system flow diagrams at or adjacent to the air-handling unit, indicating operating instructions, TAB performance, commissioning functional performance tests, and emergency shutoff procedures. These documents also should 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 constant reminder of design intent, and be readily available in case troubleshooting, expansion, or modernization is needed.

For the HVAC design to succeed, 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 service life of the installation.

Commissioning continues until the final commissioning report, approximately one year after the construction phase has been completed and the warranty phase comes to an end.

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