CHAPTER 19

ROOM AIR DISTRIBUTION EQUIPMENT

SUPPLY air outlets and diffusing equipment introduce air into a conditioned space to obtain a desired indoor atmospheric environment. Return and exhaust air are removed from a space through return and exhaust inlets (*inlet* and *outlet* are defined relative to the duct system and not the room, as shown in Figure 1). Various types of air outlets and inlets are available as standard manufactured products. This chapter describes this equipment, details its proper use, and is intended to help HVAC designers select room air distribution equipment applicable to the air distribution methods outlined in Chapter 56 of the 2007 *ASHRAE Handbook—HVAC Applications.*

Room air distribution systems can be classified according to their primary objective and the method used to accomplish that objective. The objective of any air distribution system is to condition and/or ventilate the space for occupants' thermal comfort, or to support processes within the space, or both.

Methods used to condition a space can be classified as one of the following:

- **Mixed** systems have little or no thermal stratification of air within the occupied and/or process space. Overhead air distribution is an example of this type of system.
- **Full thermal stratification** systems have little or no mixing of air within the occupied and/or process space. Thermal displacement ventilation is an example of this type of system.
- **Partially mixed** systems provide limited mixing of air within the occupied and/or process space. Most underfloor air distribution designs are examples of this type of system.
- **Task/ambient** air distribution focuses on conditioning only a portion of the space for thermal comfort and/or process control. Examples of task/ambient systems are personally controlled desk outlets and spot-conditioning systems. Because task/ambient distribution requires a high level of individual control, it is not covered in this chapter, but is discussed in Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals*. Additional design guidance is also provided in Bauman (2003).

Figure 2 illustrates the spectrum between the two extremes (full mixing and full stratification) of room air distribution strategies.

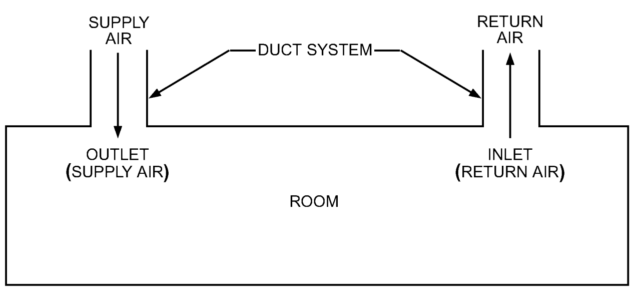

Fig. 1 Designations for Inlet and Outlet

The preparation of this chapter is assigned to TC 5.3, Room Air Distribution.

The following publications should be reviewed when selecting systems and equipment for room air distribution:

- ANSI/ASHRAE *Standard* 55-2004 establishes indoor thermal environmental and personal factors for the occupied space.
- ANSI/ASHRAE *Standard* 62.1-2007 specifies ventilation requirements for acceptable indoor environmental quality. This standard is adopted as part of many building codes.
- ANSI/ASHRAE/IESNA *Standard* 90.1-2004 provides minimum energy efficiency requirements that affect supply air characteristics.
- ANSI/ASHRAE *Standard* 113-2005 defines a method for testing the steady-state air diffusion performance of various room air distribution systems.
- Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications* recommends ranges for HVAC-related background noise in various spaces.

Local codes should also be checked for applicability to each of these subjects.

Other useful references on selecting air distribution equipment include Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals*, Chapter 56 of the 2007 *ASHRAE Handbook—HVAC Applications*, as well as Bauman (2003), Chen and Glicksman (2003), Rock and Zhu (2002), and Skistad et al. (2002).

SUPPLY OUTLETS

FULLY MIXED SYSTEMS

In fully mixed systems, supply air outlets, properly sized and located, control the air pattern to obtain proper air mixing and temperature equalization in the space.

Accessories used with an outlet regulate the volume of supply air and control its flow pattern. For example, an outlet cannot discharge air properly and uniformly unless the air enters it in a straight and uniform manner. Accessories may also be necessary for proper air distribution in a space, so they must be selected and used according to the manufacturers' recommendations.

Primary airflow from an outlet entrains room air into the jet. This entrained air increases the total air in the jet stream. Because the momentum of the jet remains constant, velocity decreases as the mass increases. As the two air masses mix, the temperature of the jet approaches the room air temperature (Rock and Zhu 2002). Outlets should be sized to project air so that its velocity and temperature reach acceptable levels before entering the occupied zone.

Outlet locations and patterns also affect a jet's throw, entrainment, and temperature equalization capabilities. Some general characteristics include the following:

- When outlets are located close to a surface, entrainment may be restricted, which can result in a longer throw.
- When the air pattern is spread horizontally, throw is reduced.
- Outlets with horizontally radial airflow patterns typically have shorter throws than outlets with directional patterns.

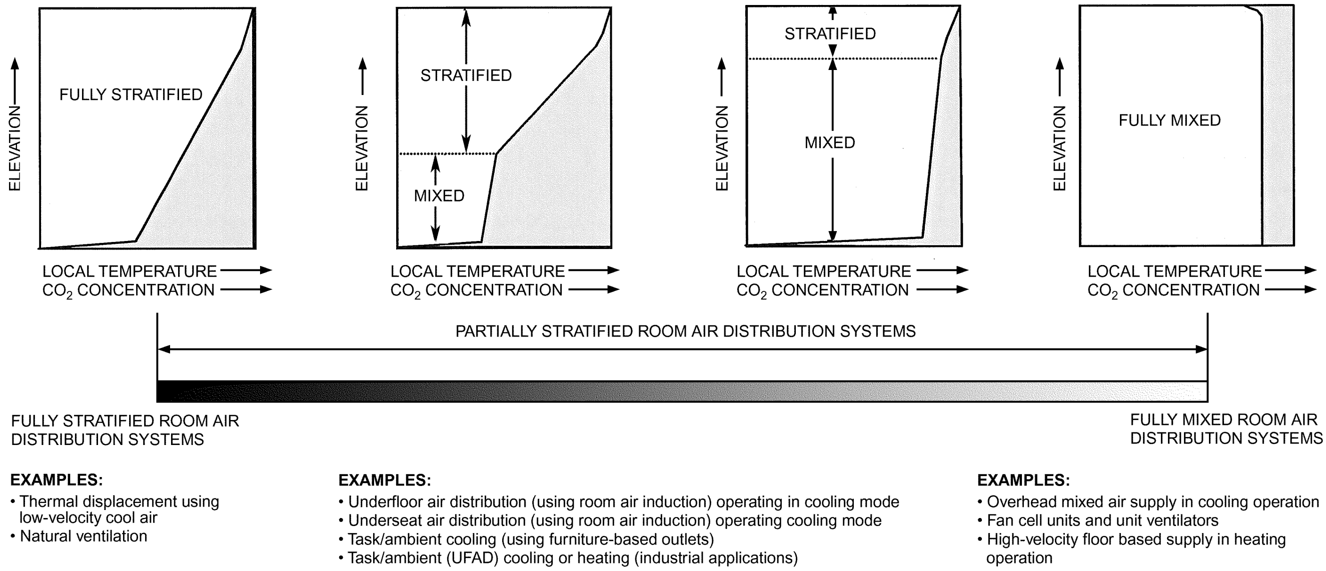

Fig. 2 Classification of Air Distribution Strategies

Ceiling or sidewall outlets in cooling applications are most commonly selected with supply air temperatures at or above 52°F. Special high-induction outlets are available for use with low-temperature air distribution systems (i.e., those with supply air temperature below 52°F). These outlets include special features that rapidly mix cold supply air with room air at the outlet and effectively reduce the temperature differential between the supply and room air. For further information, designers can consult ASHRAE's *Cold Air Distribution System Design Guide* (ASHRAE 1996).

Outlet Selection Procedure

The following procedure is generally used in selecting and locating an outlet in a fully mixed system. More details and examples are available in Rock and Zhu (2002).

1. Determine the amount of air to be supplied to each room. (See Chapters 29 and 30 of the 2005 *ASHRAE Handbook—Fundamentals* to determine air quantities for heating and cooling.)
2. Select the type and quantity of outlets for each room, considering factors such as air quantity required, distance available for throw or radius of diffusion, structural characteristics, and architectural concepts. Table 1, which is based on experience and typical ratings of various outlets, may be used as a guide for using outlets in rooms with various heating and cooling loads. Special conditions, such as ceiling height less than 8 or greater than 12 ft, exposed duct mounting, product modifications, and unusual conditions of room occupancy, should be considered. Manufacturers' performance data should be consulted to determine the suitability of the outlets used.
3. Outlets may be sized and located to distribute air in the space to achieve acceptable temperature and velocity in the occupied zone.
4. Select the proper size outlet from the manufacturers' performance data according to air quantity, neck and discharge velocity, throw, distribution pattern, and sound level. Note manufacturers' recommendations with regard to use. In an open space, the interaction of airstreams from multiple air outlets may alter a single outlet's throw, air temperature, or air velocity. As a result, manufacturers' data may be insufficient to predict air motion in a particular space. Also, obstructions to the primary air distribution pattern require special study.

Factors that Influence Selection

Coanda (Surface or Ceiling) Effect. An airstream moving adjacent to or in contact with a wall or ceiling creates a low-pressure area immediately adjacent to that surface, causing the air to remain in contact with the surface substantially throughout the length of throw. This **Coanda effect**, also referred to as the **surface** or **ceiling effect**, counteracts the drop of a horizontally projected cool airstream.

Round and four-way horizontal-throw ceiling outlets exhibit a high Coanda effect because the discharge air pattern blankets the ceiling area surrounding each outlet. This effect diminishes with a directional discharge that does not blanket the full ceiling surface surrounding the outlet. Sidewall grilles exhibit varying degrees of Coanda effect, depending on the spread of the particular air pattern and the proximity and angle of airstream approach to the surface.

When outlets are mounted on an exposed duct discharging into a free space, the airstream entrains air around the entire perimeter of the jet. As a result, a higher rate of entrainment is obtained and the isothermal throw is shortened by approximately 30%. When outlets are installed on exposed ducts for cooling applications, the supply air tends to drop. Outlets can be selected to counteract this effect.

Multiple parallel jets in close proximity tend to combine into a single jet, increasing the throw distance of the combined jet. More information on this subject can be found in Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals.*

Temperature Differential. The greater the temperature differential between the supply air projected into a space and the air in the space, the greater the buoyancy effect on the path of the supply airstream. Because heated, horizontally projected air rises and cooled air falls, consideration should be given to this effect during outlet selection. See Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* for further discussion of the buoyancy effect.

Low-temperature supply air or cold building start-up in a humid environment may cause condensation. Consideration should be given to the effect of condensation on outlet and space surfaces during outlet selection.

Sound Level. The sound level from an outlet is largely a function of its discharge velocity and transmission of system noise. For a given air capacity, a larger outlet has a lower discharge velocity and corresponding lower generated sound. A larger outlet also allows a higher level of sound to pass through the outlet, which may appear as outlet-generated noise. High-frequency noise can result from excessive outlet velocity but may also be generated in the duct by the moving airstream. Low-frequency noise is generally mechanical equipment sound and/or terminal box or balancing damper sound transmitted through the duct and outlet to the room.

The cause of the noise can usually be pinpointed as outlet or system sounds by removing the outlet core during operation. If the noise remains essentially unchanged, the system is the source. If the noise is significantly reduced, the outlet is the source. The noise may be caused by a highly irregular velocity profile at the entrance to the outlet. The velocity profile should be measured. If the velocity varies less than 10% in the air outlet entrance neck, the outlet is causing the noise. If the velocity profile at the entrance indicates peak velocities significantly higher than average, check the manufacturer's data for sound at the peak velocity. If this value approximates the observed noise, the velocity profile in the duct must be corrected to achieve design performance.

Smudging. Smudging is the deposition of particles on the air outlet or a surface near the outlet. Particles are entrained into the primary discharge jet and impinged into the device or ceiling surface in areas of lower pressure. Smudging tends to be heavier in high-traffic areas near building entrances, where particulates are brought into a space on the bottom of occupants' shoes. In well-maintained systems, filtered supply air contributes little to ceiling smudging. Smudging is typically more prevalent with ceiling-mounted outlets and linear outlets that discharge parallel to the mounting surface than with outlets that discharge perpendicular to the surface.

Variable Air Volume. Outlet(s) should be selected based on the total range of airflow for the space served. Outlet performance characteristics should be evaluated at both the minimum and maximum flow. More information regarding selection of outlets can be found in Chapter 56 of the 2007 *ASHRAE Handbook—HVAC Applications*.

FULLY STRATIFIED SYSTEMS

Stratified room air distribution systems generally rely on supply outlets with very low discharge velocities (70 to 80 fpm based on total face area) to produce minimal room air entrainment so that much of the temperature difference between supply and ambient air is preserved. Thus, cool supply air accumulates in the lower levels of the space. Horizontal movement of air in the space occurs at minimal velocities that are insufficient to produce mixing with room air; thus, the supply airstream maintains its thermal integrity. Heat sources in the space create convection plumes that originate around the boundaries of the heat source and rise naturally because of their buoyancy. If these sources are near the supply airstream, supply air is entrained to fill the void of the rising convection plume.

Although the supply airstream is several degrees cooler than the room air when it enters the occupied zone, the temperature differential between supply and room air is generally less than that commonly used for fully mixed systems. Stratified systems used in transient spaces such as transportation terminals, lobbies, and industrial spaces may, however, use air temperature differentials similar to those in fully mixed systems.

Outlet Selection Procedure

Supply outlets used in stratified air systems tend to be mounted in low sidewall or floor locations. To produce adequately low discharge velocities, the outlets also tend to be quite large. Because discharge velocities are very low, the supply airstream produces little momentum, and obstacles (other than heat sources) in its path have little or no effect on its travel. Selection and application of air outlets for these systems is based primarily on the following considerations:

- Maintaining **vertical temperature gradients** within the occupied space that conform to ASHRAE *Standard* 55-2004. Further guidance on designing for conformance to this standard is presented in Chapter 56 of the 2007 *ASHRAE Handbook—HVAC Applications*.
- Maintaining a **near zone** adjacent to the outlets that is acceptable to the use and occupancy of the space.
- Providing **acoustical performance** that conforms to the requirements of the space.

Supply outlets used in fully stratified systems are typically selected for a maximum face velocity of 70 to 80 fpm. Limitation of the face velocity is determined by noise requirements and proximity of occupants to the outlet. Where space noise requirements are not so stringent and stationary occupants are far away from diffusers, higher face velocities can be used. It is also important that the supply air outlet be designed to distribute airflow evenly across its entire discharge area to avoid excessive velocity deviations.

The area adjacent to the supply outlet where local velocities may exceed 40 fpm is defined as the near zone, where local velocity/temperatures may combine to create drafty conditions. Manufacturers of outlets specifically intended for fully stratified systems publish predicted near-zone values that depend on the outlet supply airflow rate and the initial temperature difference between the supply and room air. Stationary occupants should not be located in the near zone.

For applications requiring very low noise criteria, such as broadcast or recording studios or performing arts venues, acoustical performance can be an important consideration. Because of their low velocity discharge, these supply outlets can generally be selected to meet acoustical criteria for these applications.

Factors that Influence Selection

Space Considerations. To maximize system efficiencies, the preferred locations for supply outlets are in the low sidewall or floor. These supply outlets typically take up considerably more space than outlets used in fully mixed systems. To increase the face area, these outlets are often configured as quarter-round, semicircular, or cylindrical outlets. The latter configuration is generally mounted in open space, whereas the other configurations mentioned are mounted in corners or adjacent to the sidewall, respectively.

Space Heating Considerations. Skistad et al. (2002) reported that displacement ventilation can be combined successfully with radiators and convectors at exterior walls to offset space heat losses. Radiant heating panels and heated floors also can be used with displacement ventilation. When a secondary heating system is used, displacement outlets can supply air with a supply-to-room cooling differential as low as 4°F and still maintain a displacement airflow to the space.

When warm air is supplied through displacement outlets, its performance is similar to a fully mixed system in a heating application.

System and Terminal Considerations. Low-velocity supply air outlets used in fully stratified systems can function properly with either constant- or variable-air-volume (VAV) supply air systems. For VAV applications, the supply air volume should be determined by a thermostat located in the space at a height of four to five feet. Because stratification results in cooler temperatures below the thermostat, its set point can be maintained 2.5 to 3°F warmer than is typical in fully mixed systems.

When fully stratified systems are applied in humid climates, the use of series fan-powered terminal units or other mixing zone devices may allow supply air to be delivered from the central HVAC system at conventional temperatures and then blended with return/plenum air in the terminal to bring the air to an appropriate discharge temperature. However, this may compromise the space contaminant removal benefits of the displacement system.

PARTIALLY MIXED SYSTEMS

Partially mixed room air distribution systems are those whose design intent is to create mixed conditions in a portion of the room while maintaining thermal stratification in the remainder of the space. Supply outlets for these systems are usually designed and selected to discharge cool supply air from low sidewall or floor locations. These outlets produce high room air entrainment such that velocity and temperature differentials between supply and room air can be quickly dissipated. This results in relatively well-mixed room air conditions in some or all of the occupied space, while stratified conditions are maintained throughout the remainder. Although most underfloor air distribution systems should be classified as partially mixed systems, underfloor air delivery can also produce fully mixed or fully stratified room air distribution.

Because supply air is introduced in the occupied zone, the supply air temperature is generally 62 to 65°F for cooling.

Outlet Selection Procedures

Supply outlets used in partially mixed air systems tend to be mounted in the low sidewall or floor. They may also be mounted in the floor or risers beneath seats in public assembly facilities. Because of their high degree of mixing supply and room air, these outlets can be selected for much higher discharge velocities than those used in fully stratified systems, resulting in significantly smaller outlet discharge areas. Selection and application of air outlets for partially mixed systems is based primarily on the following considerations:

- Maintaining **vertical temperature gradients** in the occupied space that conform to ASHRAE *Standard* 55-2004. Further guidance on designing for conformance to this standard is presented in Chapter 56 of the 2007 *ASHRAE Handbook—HVAC Applications*.
- Maintaining a **near zone** adjacent to the outlets that is acceptable to the use and occupancy of the space.
- Providing **acoustical performance** that conforms to the requirements of the space.

Supply outlets should be selected such that their vertical projection achieves comfort and ventilation objectives. Limiting the vertical projection (to a terminal velocity of 50 fpm) of the supply air to below the respiration level allows convective heat plume formation around occupants to convey respiratory contaminants out of the occupied zone. This creates breathing-level CO_2 concentrations similar to those associated with fully stratified room air distribution systems. Projections that exceed this level discourage formation of such plumes and result in space ventilation similar to that of fully mixed systems.

The area adjacent to the supply outlet where local velocities may exceed 40 fpm is defined as the near zone. This is the area where local velocity/temperatures may combine to create drafty conditions. Manufacturers of outlets specifically intended for partially mixed systems publish predicted near-zone values that depend on the outlet supply airflow rate and the initial temperature difference between supply and room air. Stationary occupants should not generally be located in the near zone.

For applications requiring very low noise criteria, such as broadcast or recording studios or performing arts venues, acoustical performance can be an important consideration. These supply outlets may be suitable to meet acoustical criteria for these applications.

Factors that Influence Selection

Space Considerations. Partially mixed air distribution systems often rely on a pressurized plenum to deliver conditioned air to the supply air outlets; therefore, most of these outlets are not individually ducted. For example, underfloor air distribution systems commonly use the cavity beneath a raised access floor as a pressurized plenum. The supply outlets are mounted in the access floor tiles and can easily be relocated in response to space changes and workstation relocation.

Most supply outlets used in pressurized floor plenum applications can be easily adjusted for airflow by the space occupant. In such applications, it is usually effective to provide an adjustable outlet in every office or workstation to afford occupants control of their own environment. Many of these outlets can also be fitted with a thermostatically controlled damper that provides variable air volume to the space.

System and Terminal Considerations. Supply air outlets designed specifically for partially mixed room air distribution systems can function properly with either constant- or variable-air-volume (VAV) systems. For VAV applications, the supply air volume should be determined by a thermostat located in the space at a height of four to five feet. Because stratification typically results in cooler temperatures below the thermostat, its set point can usually be maintained slightly warmer than is typical in fully mixed systems.

TYPES OF SUPPLY AIR OUTLETS

Table 1 introduces the types of supply air outlets and provides guidance for best use practices. This table is for guidance only; designers should consult manufacturers' literature for additional application information.

Grilles

A supply air grille usually consists of a frame enclosing a set of either vertical or horizontal vanes (for a single-deflection grille) or both (for a double-deflection grille). These are typically used in sidewall, ceiling, sill, and floor applications.

Types.

Adjustable-Blade Grille. This is the most common type of grille used as a supply outlet. A single-deflection grille includes a set of either vertical or horizontal vanes or blades. Vertical vanes deflect the airstream in the horizontal plane; horizontal vanes deflect the airstream in the vertical plane. A double-deflection grille has a second set of vanes typically installed behind and at right angles to the face vanes, and controls the airstream in both the horizontal and vertical planes.

Fixed-Blade Grille. This grille is similar to the adjustable-blade grille except that the vanes or blades are not adjustable and may be straight or angled. The angle(s) at which air is discharged depends on the deflection of the vanes.

Linear Bar Grille. This outlet has fixed bars at its face. The bars normally run parallel to the length of the outlet and may be straight or angled. These devices supply air in a constant direction and are usually attached to a separate supply air plenum that has its own inlet. Linear bar grilles can be installed in multiple sections to achieve long, continuous lengths or installed as a discrete length. Typically designed for supply applications, they are also commonly used as return inlets to provide a consistent architectural appearance. Also commonly used in underfloor air distribution systems, some linear bar grilles allow the discharge pattern to be changed using removable cores. Many also incorporate a damper/actuator for automatic control of the supply air volume by a space thermostat.

Accessories. Various accessories, designed to modify the performance of grille outlets, are available:

- **Dampers** should be attached to the backs of grilles or installed as separate units in the duct to regulate airflow. (The combination of a supply air grille and a damper is called a **register**.) **Opposed-blade** damper vanes rotate in opposite directions (Figure 3A) **Parallel-blade** damper vanes rotate in the same direction (Figure 3B). Dampers deflect the airstream, and when located near the grille, they may cause nonuniform airflow and increase pressure drop and sound.
- **Extractors** are installed in collar connections to the outlet and are used to improve the flow distribution into the grille or register. The device shown in Figure 3C has vanes that pivot such that the supply airflow to the grille or register remains perpendicular to the face of the outlet. The device shown in Figure 3D has fixed vanes. Both devices restrict the area of the duct in which they are installed and should be used only when the duct is large enough to

Table 1 Typical Applications for Supply Air Outlets

Outlet Types	Fully Mixed			Fully Stratified		Partially Mixed		
	Ceiling Mounted	Wall Mounted	Floor/Sill	Wall Mounted	Floor/Sill	Ceiling Mounted	Wall Mounted	Floor/Sill
Grilles								
Adjustable blade	◒	●	⊗	⊗	⊗	⊗	⊙	⊙
Fixed blade	⊙	◒	⊗	◒	⊙	⊗	⊙	⊗
Linear bar	⊗	●	●	⊙	⊙	⊗	⊙	●
Nozzle	◒	●	⊗	⊗	⊗	⊗	⊗	⊗
Diffusers								
Round	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Square	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Perforated face	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Louvered face	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Plaque face	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Hemispherical	⊗	⊗	⊗	⊗	⊗	●	⊗	⊗
Laminar flow	⊗	⊗	⊗	⊗	⊗	●	⊗	⊗
Variable geometry	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Linear slot	●	●	⊗	⊗	⊗	⊗	⊗	⊗
T-bar slot	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Light troffer	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Swirl	●	⊗	⊗	⊗	◒	⊗	●	●
Displacement	⊗	⊗	⊗	●	●	⊙	⊗	⊗
Active chilled beam	●	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Air dispersion duct	◒	⊗	⊗	⊗	⊗	●	⊗	⊗

● = often used ◒ = sometimes used ⊙ = seldom used ⊗ = not recommended

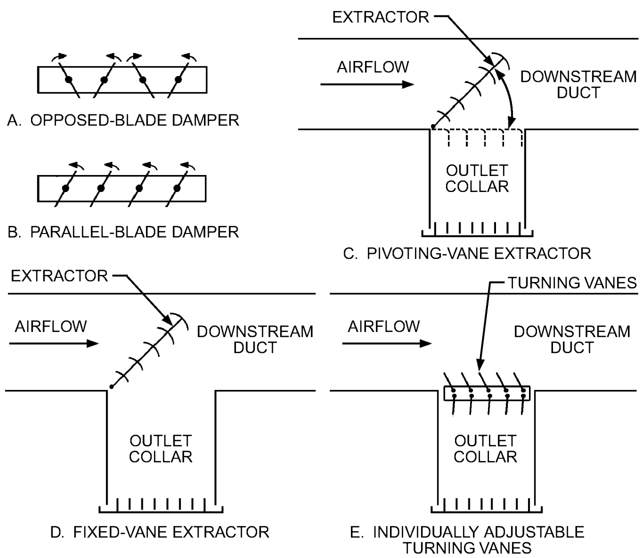

Fig. 3 Accessory Controls for Supply Air Grilles

allow the device to open to its maximum position without unduly restricting airflow to the downstream duct. These devices may increase the system pressure requirement, thereby limiting downstream airflow and increasing the sound level.

- The device shown in Figure 3E has individually **adjustable vanes**. Typically, two sets of vanes are used. One set equalizes flow across the collar, and the other set turns the air. The vanes should not be adjusted to act as a damper, because balancing requires removing the grille to gain access and then reinstalling it to measure airflow.
- Other miscellaneous accessories, such as **remote control devices** to operate the dampers, and **travel limit stops**, are also available.

Applications. Typically, supply air grilles are used in high-sidewall, ceiling, sill, or floor applications.

High Sidewall. An adjustable double-deflection grille usually provides the most satisfactory solution. The vertical louvers of the grille can be set for approximately 50° maximum deflection to either side, which can usually cover the conditioned space. Horizontal louvers can be set to control the elevation of the discharge pattern. Upward deflection minimizes thermal drop in cooling applications.

Ceiling. Such installation is generally limited to grilles with curved vanes that discharge parallel to the mounting surface. For high mounting locations (greater than 10 ft above the occupied zone), vertical discharge may be the preferred application. Grilles installed in 8 to 10 ft high ceilings, discharging the airstream into occupied zone, usually result in unacceptable comfort conditions. Satisfactory performance can be obtained if special allowances are made for terminal velocities and temperature differentials in the occupied space. Grille or register selections for heating and cooling applications from the same device should be carefully examined for use in both applications.

Sill. Linear bar grilles are commonly used in sill applications. The grille should be installed with the supply air jet directed vertically away from the occupied space. When the device is mounted 12 in. or less from the wall, a device with 0° deflection is suitable. If the device is installed more than 12 in. from the vertical surface, a linear bar grille with a fixed 15 to 30° deflection is recommended. This device should be installed with the jet directed toward the wall. These grilles are typically available with doors or other means of access to mechanical equipment that may be installed in the sill enclosure. The presence of window draperies or blinds and the effect of an impinging airstream must be considered in the selection.

Floor. Linear bar grilles are typically used for floor applications. The designer should determine the traffic and floor loading on the grille and consult the manufacturer's load limit for the grille. The grille should be placed in low-traffic areas. A floor-mounted grille is usually selected to discharge supply air along a wall or exterior surface. A floor grille is appropriate along exterior surfaces for heating. The grille should be installed with the supply air jet directed vertically away from the occupied space. When the device is mounted 12 in. or less from the wall, a device with 0° deflection is suitable.

If the device is installed more than 12 in. from the vertical surface, a linear bar grille with a fixed 15 to 30° deflection is recommended. This device should be installed with the jet directed toward the wall. The presence of window draperies or blinds and the effect of an impinging airstream must be considered in the selection.

Nozzles

Ball, drum, and other simple, usually adjustable nozzles allow air jets to be directed. These devices typically have no or few vanes in their airflow paths. Low pressure losses, moderate sound generation, and long throws are commonly produced by nozzles. They are often installed in buildings as horizontally discharging high-sidewall outlets, or in fur-downs (interior duct soffits). Nozzles are typically used in large spaces. Aircraft and automobile ventilation systems also use these types of outlets (Rock and Zhu 2002).

The equations in Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* can be used to estimate throw from many such simple duct terminations or orifices. For complex situations, physical experiments or computational fluid dynamics (CFD) modeling may be helpful in selection and design.

Diffusers

Diffusers usually generate a radial or directional discharge pattern. For ceiling applications, this pattern is typically parallel to the mounting surface. Diffusers may also include adjustable deflectors that allow discharge to be directed perpendicular to the mounting surface. A diffuser typically consists of an outer shell, which contains a duct collar, and internal deflector(s), which define the diffuser's performance, including discharge pattern and direction.

Types.

Round Diffuser. This diffuser is a series of concentric conical rings, typically installed either in gypsum-board ceilings or on exposed ducts. Round ceiling diffusers are available in a broad range of sizes and capacities, with adjustable inner cones that allow the diffuser to discharge air either parallel or perpendicular to the ceiling or mounting surface.

Square Diffusers. This diffuser is consists of concentric square, drawn louvers that radiate from the center of the diffuser. Available with faces that are flush with the ceiling plane or with dropped inner cones, these diffusers have a fixed horizontal radial discharge pattern or an adjustable discharge pattern that allows the direction to be either horizontal or vertical. Special borders can be selected to accommodate various mounting applications.

Perforated Diffuser. This diffuser consists of a duct collar and a single perforated plate that forms the diffuser's face, with typical free area of about 50%. The perforated face tends to create a slightly higher pressure drop and sound than other square ceiling diffusers. They are available with deflection devices mounted at the neck or on the face plate. The deflectors may be adjustable, to provide horizontal air discharge in one, two, three, or four directions. Special borders can be selected to accommodate various mounting applications.

Louvered-Face Diffuser. This diffuser consists of an outer border, which includes an integral duct collar, and a series of louvers. Louvered-face diffusers typically provide a horizontal discharge perpendicular to the louver length. The louvers may be arranged to provide four-way, three-way, two-way opposite, two-way corner, or one-way discharge. Special borders can be selected to accommodate various mounting applications. Some louvered-face diffusers are available with adjustable louvers that can change the discharge direction from horizontal to vertical.

Plaque-Face Diffuser. This diffuser is constructed with a duct collar and a single plaque that forms the diffuser's face. This air outlet typically has a horizontal, radial discharge pattern. Typically, performance is similar to that of a square-face, round-neck diffuser. Special borders can be selected to accommodate various mounting applications.

Hemispherical Flow Diffuser. This diffuser provides a vertically radial air discharge pattern. The discharge penetrates the conditioned space perpendicular to the mounting surface. These diffusers are typically used for applications needing high air change rates, and/or low local velocities. Some outlet models are flush to the mounting surface; others intrude into the space below the ceiling. Most function similarly with or without an adjacent ceiling surface.

Laminar-Flow Diffuser. This diffuser provides a unidirectional discharge perpendicular to the mounting surface. The free area of the perforated face is typically less than 35%. Most outlets include a means to develop a uniform velocity profile over the full face. This minimizes mixing with surrounding ambient air and reduces entrainment of any surrounding contaminants. These diffusers are typically used in hospital operating rooms, cleanrooms, or laboratories.

Variable-Geometry Diffuser. This diffuser assembly can vary its discharge area in response to changes in space temperature or supply air temperature. As the terminal's airflow rate changes, the diffuser's discharge area can change to minimize changes in the diffuser's throw.

Linear Slot Diffuser. Long and narrow, linear slot diffusers may be installed in multiple sections to achieve long, continuous lengths or installed as a discrete length. They can consist of a single slot or multiple slots, and are available in configurations that provide vertical to horizontal airflow. Typically, a supply air plenum is provided separately and attached during installation. Other applications include field mounting the linear slot diffuser directly into a supply duct.

T-Bar Slot Diffuser. This diffuser is manufactured with an integral plenum and normally is installed in modular T-bar ceilings. Available with either fixed-deflection or adjustable-pattern controllers, these devices can discharge air from fully vertical to fully horizontal.

Light Troffer Diffuser. A light troffer diffuser serves as the combined plenum, inlet, and attachment device to an air-handling light fixture, which has a slot to receive the diffuser at or near the face of the lighting device, to discharge supply air into the space. Normally, only the air-handling slot is visible from the occupied space.

Swirl Diffuser. These diffusers feature a series of linear openings arranged in a radial pattern around the center of the diffuser face. This promotes a high degree of entrainment of room air, resulting in very high induction ratios, which maximize mixing in the area adjacent to the diffuser face. Swirl diffusers may be mounted in ceiling, sidewall, or floor locations. When mounted in floor locations, care should be taken to ensure that the diffuser can meet the floor loading requirements.

Displacement Diffuser. Typically located in floor or sidewall locations, these diffusers are designed to limit discharge velocities to 70 to 80 fpm, to minimize mixing between supply and room air. These outlets tend be large, to generate the low velocities required for thermal displacement ventilation. The low-velocity discharge allows the cooler supply air to fall to the floor and remain there because of its reduced buoyancy with respect to the ambient room air above it. These outlets are available in various shapes and configurations that facilitate flush or adjacent mounting to the sidewalls or floor of the space.

Air Dispersion Duct. This outlet system is designed to both convey and disperse air within the space being conditioned. Diffusion options include outlets selected for a full range of entrainment. Typically, these systems are made of fabric, sheet metal, or plastic film.

Active Chilled Beams. These devices typically use integral slot diffusers as their supply air outlets in a fully mixed room air distribution system.

Accessories. Various performance-modifying devices are available for use with diffusers:

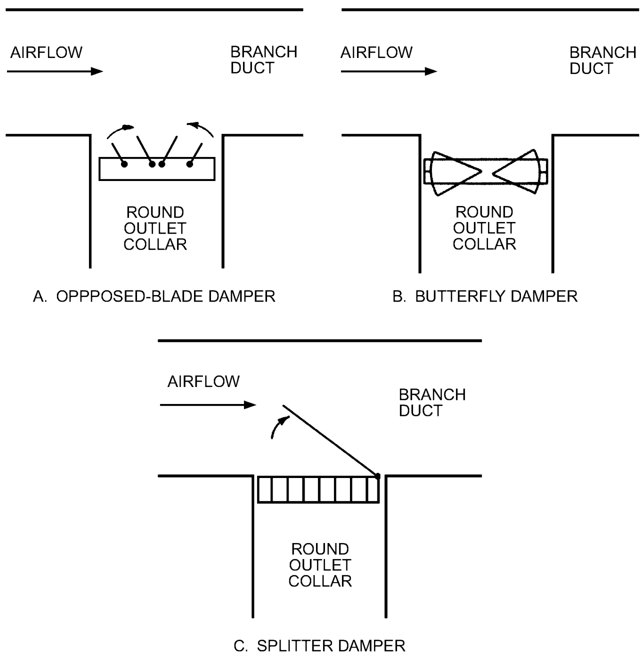

Fig. 4 Accessory Controls for Ceiling Diffusers

- **Dampers** can be attached to the inlets of diffusers or installed as separate units in the duct, to regulate the volume of air being discharged. **Opposed-blade** damper vanes rotate in opposite directions (Figure 3A) and are available for round, square, or rectangular necks. **Parallel-blade** dampers rotate in the same direction (Figure 3B). **Adjustable-vane** dampers have individually adjustable vanes (Figure 4A). **Butterfly** dampers are constructed with opposing damper plates that move in opposite directions and are adjusted from a center point (Figure 4B). A **splitter** damper is a single-blade device, hinged at one edge and usually located at the branch connection of a duct or outlet (Figure 4C). The device is designed to allow adjustment at the branch connection of a duct or outlet to adjust flow. **Radial** dampers are made up of multiple overlapping flat blades that rotate in the horizontal plane to deflect the airstream. When installed on the diffuser inlet, these dampers are operated through the face of the diffuser. When these dampers are located near the grille, they may cause nonuniform airflow and increase pressure drop and sound. Refer to Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications* for the effects of damper location on sound level.
- **Equalizing** or **flow-straightening devices** or **grids** allow adjustment of the airstream to obtain more uniform flow to the diffuser.
- **Other balancing devices** are available. Consult manufacturers' literature as a source of information for other air-balancing devices.

Applications. For the following applications, the manufacturer's catalog data should be checked to select the air outlet that meets throw, pressure, and sound requirements.

Perimeter Zone Ceiling. In perimeter ceiling applications, the air outlet must handle the exterior surface load as well as the interior zone load generated along the perimeter. Refer to Chapter 56 of the 2007 *ASHRAE Handbook—Applications* for more details.

Interior Zone Ceiling. Typical interior ceilings require an air outlet that produces a horizontal pattern along the ceiling. Many ceiling diffusers are well suited for this application. Selection can be made based on performance, appearance, and cost. The air outlet selected should be sized to keep the supply air jet away from the occupied zone.

Vertical Projection. Downward projection of air from the outlet is often required in a high-ceiling application or in a high-load area. Vertical projection may be selected to meet an individual's comfort requirements. When selecting an outlet for vertical projection for both heating and cooling, its performance under both conditions must be taken into consideration. This is especially necessary when air outlet discharge characteristics are not automatically changed from heating to cooling.

Spot Heating or Cooling. Spot heating or cooling typically requires using an outlet that projects the air jet to a specific location. When selecting an outlet for both heating and cooling, its performance under both conditions must be taken into consideration. This is especially necessary when air outlet discharge characteristics are not automatically changed when switching, from heating to cooling.

Exposed Duct. In exposed-duct (no ceiling) applications, most ceiling diffusers can be used; however, the throw or radius of diffusion should be derated to allow for the influence of obstructions. Other approaches for exposed-duct applications include using perforated and/or fabric ducts.

RETURN AND EXHAUST AIR INLETS

Return air inlets may either be connected to a duct or simply cover openings that transfer air from one area to another. Exhaust air inlets remove air directly from a building and, therefore, are most always connected to a duct. Velocity, sound, and pressure requirements for inlets are determined by size and configuration. In general, the same type of equipment, grilles, slot diffusers, and ceiling diffusers used for supplying air may also be used for air return and exhaust. However, inlets do not require the deflection, flow equalizing, and turning devices necessary for supply outlets.

TYPES OF INLETS

For discussion of **adjustable-blade**, **fixed-blade**, and **linear bar grilles**, see the section on types of supply air outlets.

V-Bar Grille

Made with bars in the shape of inverted Vs stacked within the grille frame, this grille has the advantage of being sightproof. Door grilles are usually v-bar grilles. The airflow capacity of the grille decreases with increased sight-tightness.

Lightproof Grille

This grille is used to transfer air to or from darkrooms. The bars of this type of grille form a labyrinth and are painted black. The bars may be several sets of v-bars or be an interlocking louver design to provide the required labyrinth.

Stamped Grilles

Stamped grilles are also frequently used as return and exhaust inlets, particularly in restrooms and utility areas.

Eggcrate and Perforated-Face Grilles

These return grilles typically have large free areas. Perforated grilles often have free areas around 50%; eggcrate grilles can exceed 90% free area.

APPLICATIONS

Return and exhaust inlets may be mounted in practically any location (e.g., ceilings, high or low sidewalls, floors, and doors). To fully obtain their inherent contaminant removal benefits, return and exhaust opening serving spaces conditioned by fully stratified and partially mixed systems should always be located above the occupied zone. Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* and Rock and Zhu (2002) discuss factors and the effect of inlet location on the system.

Dampers like the one shown in Figure 3A are sometimes used in conjunction with grille return and exhaust inlets to aid system balancing.

TERMINAL UNITS

In air distribution systems, special control and acoustical equipment is frequently required to introduce conditioned air into a space properly. Airflow controls for these systems consist principally of terminal units (historically called “boxes”), with which the airflow can be varied by pressure-modulating valves, fan controls or both. Terminal units may be classified as single or dual duct, with or without cooling, fans, heat or reheat, and having either constant or variable primary airflow rate. The constant primary air volume may provide for a variable discharge air volume to the conditioned space. Terminal units may employ plenum or room air induction to affect space temperature control while maintaining a constant or variable discharge airflow rate. Terminal units often include sound attenuators, or heaters, reheaters, or cooling coils.

This section discusses control equipment for single- and dual-duct air conditioning systems. Chapter 18 covers duct construction details. Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications* includes information on sound control in air-conditioning systems and sound rating for air outlets.

General

Terminal units are factory-made assemblies for air distribution. A terminal unit manually or automatically performs one or more of the following functions: (1) controls air velocity, pressure, or temperature; (2) controls airflow rate; (3) mixes airstreams of different temperatures or humidities; (4) mixes, within the assembly, primary air from the duct system with air from the treated space or from a secondary duct system; and (5) heats or cools the air. To achieve these functions, terminal unit assemblies are made from an appropriate selection of the following components: casing, mixing section, manual or automatic damper, heat exchanger, induction section (with or without fan), coils, and flow controller.

A terminal unit may include a sound attenuation chamber to reduce sound. At the same time, the terminal unit can reduce velocity and pressure at the inlet to a lower velocity and pressure. The sound attenuation chamber is typically lined with thermal and sound insulating material and may be equipped with baffles.

Additional sound absorption material may be required in low-pressure distribution ducts connected to the discharge of larger units. Smaller units may not require additional sound absorption; however, manufacturers’ catalogs should be consulted for specific performance information.

Terminal units are typically classified by the function of their flow controllers, which are generally constant- or variable-flow devices. They are further categorized as either pressure-dependent, where airflow through the assembly varies in response to changes in system pressure, or pressure-independent (pressure-compensating), where airflow through the device does not vary in response to changes in system pressure.

Variable-air-volume (VAV) reset controllers can control the VAV damper to regulate airflow to a constant fixed amount or to a variable modulating value that is calculated by the room demand. These controllers can be electric (pressure dependent), electronic (pressure independent) or pneumatic (pressure dependent or pressure independent). Pressure independent controllers require a pressure or velocity signal input to reset the VAV damper, which controls airflow. Temperature inputs are also required for calculating room demand for comfort conditioning. Variable flow may also be obtained by decreasing the flow through a constant-volume regulator with a modulating damper ahead of the regulator. This arrangement typically allows for variations in flow between the high- and low-capacity limits or between a high limit and shutoff. These units are pressure-dependent and volume-limiting in function.

Terminal units are also categorized as (1) system-powered, in which the assembly derives all the energy necessary for operation from supply air within the distribution system; or (2) externally powered, in which the assembly derives part or all of the energy from a pneumatic or electric outside source. In addition, assemblies may be self-contained (furnished with all necessary controls for their operation, including actuators, regulators, motors, and thermostats or space temperature sensors) or non-self-contained assemblies (part or all of the necessary controls for operation may be furnished by someone other than the assembly manufacturer). In the latter case, the controls may be mounted on the assembly by the assembly manufacturer or mounted by others after delivery.

The damper or flow controller in the unit can be adjusted manually, automatically, or by a pneumatic or electric motor. The unit is actuated by a signal from a thermostat or flow regulator, depending on the desired function of the box.

Air from the unit may be discharged through a single opening suitable for connection to a low-pressure rigid branch duct, or through a plenum to several round outlets suitable for connecting to flexible ducts. A single supply air outlet connected directly to the discharge end or bottom of the unit is an optional arrangement; however, the acoustic performance of this close-coupled arrangement must be carefully considered.

Single-Duct Terminal Units

Single-duct terminal units can be cooling only, cooling/heating if the primary air unit provides both or reheat if a heater is present. Reheat terminal units add sensible heat to the supply air. Water or steam coils or electric resistance heaters are placed in or attached directly to the air discharge of the unit. These are single-duct or bypass units that can operate as either constant- or variable-volume units. However, if they are variable-volume, they must maintain some minimum airflow for reheat. Some have a dual minimum flow, with one minimum being either zero during the no-occupancy cooling cycle or the airflow required for minimum ventilation during the cooling cycle, and the second minimum being the capacity required for reheat capacity during the reheat cycle. This type of equipment can provide local individual reheat without a central equipment station or zone change.

Dual-Duct Terminal Units

Dual-duct terminal units are typically controlled by a room thermostat. They receive warm or neutral and cold air from separate air supply ducts in accordance with room requirements to obtain room control without zoning. Volume-regulated units have individual modulating dampers and operators to regulate the amount of warm and cool air. When a single modulating damper operator regulates the amount of both warm and cold air, a separate pressure-reducing damper or volume controller is suggested in the unit to reduce pressure and limit airflow. Specially designed baffles may be required inside the unit or at its discharge to mix varying amounts of warm and cold air and/or to provide uniform flow and temperature equalization downstream. Dual-duct units can be equipped with constant- or variable-flow devices. These are usually pressure-independent, to provide a number of volume and temperature control functions. Dual-duct terminals may also be used as outside air terminals in which the neutral air inlet is used to control and maintain the required volumetric flow of ventilation air into the space. Dual-duct units with cooling and neutral air may need a local heating device.

Air-to-Air Induction Terminal Units

Induction terminals supply primary air or a mixture of primary and recirculated air to the conditioned space. They achieve this function with a primary air orifice that induces air from the ceiling plenum or individual rooms (via a return duct). Primary air cool enough to satisfy zone design cooling loads is ducted to the terminal The induction unit contains dampers that are actuated in response to a thermostat, to modulate the mixture of cool primary air and warm induced air. As less cooling is required, the primary airflow is gradually reduced, as the induced air rate generally increases. To meet interior load requirements, reheat coils can be installed in the primary supply air duct.

Chilled Beams

Chilled beams may be classified as active or passive. **Active chilled beams** are ceiling-mounted induction terminals that consist of a primary air duct connection, a series of induction nozzles, a hydronic heat transfer coil, a supply outlet, and a room air inlet section. Primary air discharged through the induction nozzles entrains room air through the inlet section and across a chilled- and/or hot-water coil where it is reconditioned before being mixed into the primary airstream. The free area of the room air inlet should be as high as possible, and at a minimum 50% of its total face area. Chilled-water supply temperatures are maintained at or above the room air dew point to prevent condensation from forming on the heat transfer coil. The mixture of primary and reconditioned room air is then discharged to the room through linear slots. These terminals typically discharge a constant-volume airflow with its temperature modulated (by the room air reconditioning) in accordance with the space thermostat demand. Active chilled beams generally produce a fully mixed room air distribution.

Passive chilled beams are sheet metal enclosures that contain finned-tube (chilled-water) convection coils. They rely on thermal stratification in the space to deliver warm air to its upper boundaries, some of which enters the passive beam casing. As this air passes over the back of the passive beam, it is drawn through the chilled-water coil and much of its heat is rejected. The reduced buoyancy that results causes the cooled air to drop back into the space. Because passive beams are not connected to a supply air duct, outside supply air must be provided to the space by a separate system. Supply air outlets used with passive beams should be selected to provide a fully stratified or partially mixed room air distribution, because turbulent airflow near passive beams disturbs the natural convection currents that deliver warm air to the beams.

Fan-Powered Terminal Units

Fan-powered terminal units are used in primary-secondary HVAC systems as secondary-level air handlers, and are typically installed in return air plenums. They are also frequently used as small, stand-alone air handlers. They differ from air-to-air induction units in that they include a blower, driven by a small motor, which draws air from the space, ceiling plenum, or floor plenum, that may be mixed with the cool air from the main air handler. The advantages of fan-powered units over straight VAV units are (1) during the heating mode, the primary air is mixed with warmer plenum air to blend the air temperature entering the heater to a level at or above room temperature, thus eliminating reheat; (2) downstream air pressure can be boosted to deliver air to areas that otherwise would be short of airflow; (3) room airflow volumes can be varied to improve occupant comfort; (4) perimeter zones can be heated without operating the main air handler fan during unoccupied periods; (5) depending on construction of the building envelope, the air in the plenum may be warm enough for low to medium heating loads; and (6) main air handler unit operating pressure can be reduced with series units, reducing the air distribution system's energy consumption.

In thermal storage and other systems with supply air temperatures below 52°F, fan-powered terminal units are used to mix cold supply air with induced return or plenum air, to moderate the supply air temperature. Some units are equipped with special insulation and a vapor barrier to prevent condensation with these low supply temperatures. Manufacturers' catalogs provide further information on these special features.

Fan-powered terminal units can be divided into two categories: (1) series, with all primary and induced air passing through a blower operating continuously during the occupied mode; and (2) parallel, in which the blower operates only on demand when induced air or heat is required.

A **series** unit typically has two inlets, one for cool primary air from the central fan system and one for secondary or plenum air. All air delivered to the space passes through the blower. The blower operates continuously whenever the primary air fan is on and can be cycled to deliver heat, as required, when the primary fan is off. As cooling load decreases, a damper throttles the amount of primary air delivered to the blower. The blower makes up for this reduced amount of primary air by drawing air in from the space or ceiling plenum through the return or secondary air opening. Sometimes a series unit has two ducted inlets, like a dual-duct terminal unit, in addition to the induction air inlet. The second duct is typically used for dedicated outdoor air systems. Fan air as well as primary air can be varied when the units are in part-load condition, but fan air should never be less than the total amount of air supplied by the ducted inlets.

Parallel fan-powered terminal units bypass the cool primary air around the blower portion of the unit so that the primary air flows directly to the space. The blower section draws in plenum air and is mounted in parallel with the primary air damper. A backdraft damper keeps primary air from flowing through the blower section when the blower is not energized. The blower in these units is generally energized after the primary air damper is partially or completely throttled closed. Some electronically controlled units gradually increase fan speed as the primary air damper is throttled, to maintain constant airflow while allowing the fan to shut off when it approaches full-cooling mode. Parallel units are typically limited to one ducted supply inlet.

Fan-powered terminals in supply air plenums (for underfloor air distribution). Fan terminal units are commonly used for perimeter area heating and/or cooling in underfloor air distribution applications. Although the general operation of these terminals is very similar to that for other fan terminals, location of these terminals in the supply air plenum results in certain design and operational considerations that differentiate these fan powered terminals. Decisions regarding the employment of fan terminals and their associated ductwork in these systems should also consider their potential effect on the future relocation power, voice, and data services to the space, because these services are also housed in the supply air plenum.

Series fan-powered terminals mounted in the (underfloor) supply air plenum typically have two dampered inlets located upstream of the integral blower unit. One inlet provides conditioned supply air from either the underfloor air plenum, or ducted from the central air handling unit. The second inlet allows the integral fan to induce ducted room or return plenum air. The blower operates continuously in the occupied mode while the dampers cycle to deliver heated, cooled, or recirculated air to the space. The terminal unit fan may be modulated based on the space load.

Alternatively, perimeter areas in underfloor air distribution applications can be served by booster fan terminals that are continuously or intermittently operated. Variable-speed fan terminals can be used to vary the delivery of cool air from the supply air plenum is accordance with the cooling demand indicated by the space thermostat or building automation system. Reheat operation (using air from the supply plenum) can be accomplished with either constant or variable airflow rate. Intermittent (cycled) fan operation can be used to satisfy perimeter area heating or heating/cooling demands. Intermittent fan terminals used only for perimeter heating may be combined with variable-volume cooling terminals that deliver cool air directly from the supply air plenum. The fan (and its reheat coil) remains off during cooling operation. Intermittent fan terminals used for perimeter heating and cooling are cycled (in accordance to the space thermostat or building automation system demand) during periods of heating and cooling, delivering conditioned air from the supply air plenum, reheated as required.

Locating series terminals in the supply air plenum may significantly alter their benefits. Using return air for heat requires that a duct be provided from floor-based return air inlets to the fan terminal inlet plenum. This ductwork may create a path for excessive fan noise to be transmitted to the space. In addition, room air induced at the floor level is only slightly warmer than the alternative air source, the underfloor supply air plenum. Careful analysis of the advantage (minimal energy savings) and disadvantages (inlet ductwork potential effects on noise transmission and relocation of other services housed in the supply air plenum) of using floor level room air recirculation in this application should be performed.

Series fan-powered terminal units may also be used to mix cold supply air from a central air-handling unit with induced return air to moderate the supply air temperature for injection into the supply air plenum. This enables transport of supply air from the air handler to supply plenum inlet locations at lower temperatures and volume flow rates, which may result in smaller supply and return air ducts.

Fan-powered terminal units installed under the raised floor must be selected to fit in the space between the structural slab and the raised access floor tiles and not interfere with the floor support structure.

Bypass Terminal Units

A bypass terminal unit handles a constant supply of primary air through its inlet; with a diverting damper, it bypasses the primary air to the ceiling plenum so that the amount of cool air delivered to the conditioned space meets the thermal requirement. Bypass air is diverted into the ceiling plenum and returned to the central air handler. The pressure requirement through the supply air path to the conditioned space and through the bypass path is equalized so that the fan handles a constant flow. This method provides a low first cost with minimum fan controls, but it is energy-inefficient compared to a VAV fan system. Its most frequent application is on small systems.

REFERENCES

Rock, B.A. and D. Zhu. 2002. *Designer's guide to ceiling-based air diffusion* (RP-1065). ASHRAE.

Skistad, H., E. Mundt, P. Nielsen, K. Hagström, and J. Railio. 2002. Displacement ventilation in non-industrial premises. REHVA *Guidebook* 1. Federation of European Heating and Air-Conditioning Associations, Brussels.

BIBLIOGRAPHY

ASHRAE. 1996. *Cold air distribution system design guide* (RP-849).

ASHRAE. 2004. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard* 55-2004.

ASHRAE. 2007. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62.1-2007.

ASHRAE. 2007. Energy standard for buildings except low-rise residential buildings. ANSI/ASHRAE/IESNA *Standard* 90.1-2007.

ASHRAE. 2005. Method of testing for room air diffusion. ANSI/ASHRAE *Standard* 113-2005.

Bauman, F. 2003. *Underfloor air distribution design guide* (RP-1064). ASHRAE.

Chen, Q.Y. and L. Glicksman. 2003. *System performance evaluation and design guidelines for displacement ventilation*. ASHRAE.