energydesignresources

design brief

DISPLACEMENT VENTILATION

Summary

Displacement ventilation (DV) is an alternate air distribution method for commercial and industrial spaces.[1] Used since the late 1970s in Northern Europe and more recently in U.S. schools, DV disproves the common perception that improving indoor air quality (IAQ) in an air-conditioned space must result in higher energy consumption. By providing supply air directly to building occupants, IAQ is improved. By conditioning only the lower occupied portion of the space, cooling energy can be reduced.

This design brief provides an introduction into the design and application of DV. It addresses the following issues:

- Comparison with other air distribution systems
- Energy savings and IAQ improvements
- Typical applications
- Architectural design options
- HVAC design considerations.

DV can reduce cooling energy use in all California climates. It is especially beneficial in temperate climates, where the higher supply air temperature increases opportunities for free cooling. Schools, restaurants, theaters and auditoriums, atria, and other open spaces with high ceilings are excellent applications. It relies on a steady supply of cool air (near 65°F) at the floor to carry heat and contaminants towards the ceiling exhaust. Initial incremental costs for diffusers are offset by simplified ductwork and the possibility for a smaller chiller, often resulting in a lower total system cost.

Displacement ventilation provides improved IAQ, cooling energy savings, and better acoustics for high performance buildings.

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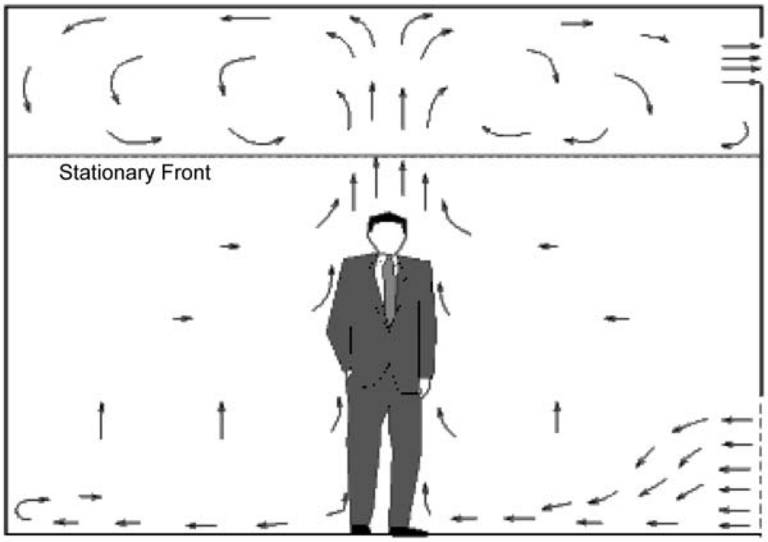
Introduction

Displacement ventilation (DV) is a means of providing cool supply air directly to the occupants in a space. The fresh air, supplied near the floor at a very low velocity, falls towards the floor due to gravity and spreads across the room until it comes into contact with heat sources. The cool supply air slowly rises as it picks up heat from occupants and equipment. The warm, stale air rises towards the ceiling where it is exhausted from the space. This vertical airflow pattern near each occupant, often referred to as a thermal plume, makes it less likely that germs will spread. The air distribution system provides for effective ventilation, since the fresh supply air is delivered directly to each occupant.

Figure 1: Displacement ventilation airflow

In a DV system, cool air pools on the floor and rises slowly as it picks up heat. Heat sources create plumes that carry away heat and contaminants towards a ceiling exhaust.



Source: Architectural Energy Corporation

How Does It Compare to Other Ventilation Systems?

In contrast, typical air distribution systems supply conditioned air from ceiling outlets at a relatively high velocity. The air is discharged at a high velocity to provide a well mixed air space.

This air distribution pattern causes contaminated room air to mix with the supply air. Most commercial buildings in the United States use this type of overhead distribution system.

A similar "sister" technology to DV, which has been successfully implemented in office buildings, is underfloor air distribution (UFAD). Although the air pattern is somewhat different than DV, the concept is similar. Air is supplied from an underfloor plenum to floor outlets at a low velocity. The air velocity with UFAD is lower than that of overhead air distribution, but the velocity and diffuser characteristics cause mixing of room air with the supply air stream. This is required due to the close proximity of the diffusers to the occupants. The result is a lower occupied air space that is fairly well mixed, but at a lower temperature than the unoccupied space. Flexibility in locating supply outlets and the ease of integrating electrical and communications wiring within the underfloor plenum make this distribution method an excellent choice for open office plans.[2] **Table 1** summarizes distribution system differences.

How Is It Achieved?

The best cooling source for a DV system is a chilled water coil. The control valve in a hydronic system allows for the supply of constant 63°F–65°F air. A typical direct expansion (DX) system is designed to provide colder 50°F–55°F air while the compressor is running and cycles on and off to meet space loads. When the compressor is off, the supply air temperature can rise to 75°F or higher. This lower temperature and larger temperature fluctuation would create a comfort problem with DV when the supply air comes in contact with occupants. However, larger DX systems with several compressors and temperature-reset capabilities will provide tighter supply temperature control and can be used as an alternative to a chilled water system. For example, a packaged rooftop variable air volume (VAV) system serving multiple spaces may be able to provide the necessary supply air temperature control.

Table 1: Air distribution system comparison

	Overhead (Mixing)	Underfloor Air Distribution (Mixing/Displacement)	Lower Wall (Displacement)
Description	Diffusers located in the ceiling deliver 55°F air at velocity of 400–700 ft per minute (fpm). Objective is a well mixed airspace.	Diffusers mounted in the floor deliver 65°F air at about 100–200 fpm velocity. Air pattern causes some mixing in the occupied space, but a higher temperature near the ceiling.	Diffusers mounted near the floor level deliver 65°F air at less than 75 fpm velocity. Air flow causes a thermally stratified space and vertical air movement towards the return.
Supply conditions	Nominally 55°F in cooling.	Typically 60°F–64°F in cooling. Some temperature rise will occur in the underfloor plenum.	Typically 63°F–68°F air in cooling.
Architectural requirements	Space above ceiling for ductwork and ceiling diffusers.	Minimum ceiling height of 8–9 ft recommended. A raised access floor is used as an air plenum and for wiring and communications. Possibility to reduce floor-to-floor height slightly.	Minimum ceiling height of 9 ft is recommended. Higher ceilings are preferred. Diffusers may take up some wall space. Floor-to-floor height is not necessarily impacted.
Thermal comfort	Even temperatures throughout the space in cooling with proper design.	Good thermal comfort with proper airflow. Potential for individual temperature control.	Very good thermal comfort in cooling with proper design. Some potential for drafts near the diffusers.
Ventilation effectiveness	FAIR—Supply air mixes with room air to dilute contaminants.	GOOD—Better than overhead distribution, but some mixing occurs in the occupied zone.	VERY GOOD—Supply air is delivered directly to occupants, and contaminants are displaced to the upper unoccupied zone.
Acoustic performance	Diffusers can be a noise source if the air velocity is too high.	Quieter due to low air velocity.	Also quieter due to lower air velocity at the diffusers.
Applications	Any.	Offices or any space with open floor plans.	Schools, restaurants, theaters, atria, and other spaces with high ceilings.

Source: Architectural Energy Corporation

DV diffusers are available in a variety of configurations to meet architectural and space requirements. The air from a DV system is typically supplied from diffusers that are surface-mounted against the interior walls of the space. Because of the requirement for very low air velocity, the diffusers take up a considerable amount of space (roughly 1 ft^2 of wall space for every 75 cfm of supply air). Manufacturers also make diffusers that are recessed into the wall. There is also an opportunity to integrate the diffusers with casework. Many of the designs can be seamlessly integrated into the architecture of the space.

Benefits

With the appropriate design and application, DV provides several benefits: improved indoor air quality, reduced energy use, and improved acoustic performance. There also may be an opportunity to reduce the capacity of the primary cooling system.

Improved Indoor Air Quality

With DV, air is supplied near the floor of the space. The cool supply air spreads across the floor of the space until it comes into contact with occupants. Since the air moves at a low velocity, the cool supply air has little chance to mix with warmer room air before reaching the occupants. The air is heated as it passes by occupant heat sources and begins to rise. Contaminated air is carried out of the breathing zone by convective thermal plumes and removed at the ceiling exhaust. Compared to overhead mixing ventilation, outside air is distributed more effectively to the occupants. Potential problems of "dumping" or short-circuiting of supply air are avoided.

The distribution of outside air in occupied spaces is characterized by ventilation effectiveness. This is a measure of how effectively the ventilation air reaches the occupants. American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62.1-2004, which refers to this as air distribution effectiveness, assumes a DV effectiveness of 1.2. This means DV provides the same IAQ as a mixing ventilation system that uses a 20 percent greater outside air volume.

ASHRAE Standard 62.1-2004 provides guidelines on required ventilation levels for acceptable IAQ and includes a description of ventilation effectiveness. More information may also be found in EDR's Indoor Air Quality Design Brief.

The vertical flow pattern towards the ceiling exhaust promotes removal of heat-borne contaminants and will result in an improved IAQ in the occupied zone. Ventilation effectiveness is also used to quantify the effectiveness of the ventilation system at removing airborne contaminants. Carbon dioxide is an indicator of the effectiveness of ventilation in diluting airborne contaminants, and is used in demand-controlled ventilation applications. Thus, carbon dioxide measurements can be used to estimate ventilation effectiveness (see **Figure 2** sidebar).

Rather than simply diluting contaminants with overhead supply air, the cool supply of air near the floor displaces the contaminants and carries them towards the ceiling by convective thermal plumes. As a result, the CO_2 concentration in the occupied zone is lower than that at the return grille where air leaves the space. This benefit has been demonstrated in K–12 classroom applications throughout the United States (see **Figure 3**).

Another benefit of DV is that the economizer can operate more often, due to the higher supply air temperature. The DV system can use 100 percent outside air more frequently, further improving IAQ.

Energy Savings

DV uses a significantly higher supply air temperature (SAT) in cooling than traditional ventilation systems. Some assert that with a higher SAT the lower "delta T" means that a large increase in supply airflow is required to remove the heat load. However, with DV the room air is not well mixed. Typically, the return air temperature is 4°F–5°F higher than the air temperature at the thermostat. A temperature differential of about 15°F between the supply and return is common. As a result, the DV design airflow is only about 20–25 percent higher than in a comparable overhead mixing system. Other characteristics of the DV system will tend to lower fan energy use. The lower air velocity reduces the system pressure drop. This allows the fan to operate more efficiently, resulting in lower fan power consumption per cfm of airflow. Despite a slightly higher design airflow, the required fan power is comparable to that required for the mixing system.

Cooling energy savings with DV has many contributing factors. The primary benefit is the increased period during which the economizer can operate. This makes a big difference in temperate

Figure 2: Ventilation effectiveness

Ventilation effectiveness is a term used interchangeably to describe either air distribution effectiveness or contaminant removal effectiveness. Air distribution effectiveness (or air change effectiveness) can be represented by the mean age of air:

$$\eta = \frac{Mean\_Age\_Air\_exhaust}{Mean\_Age\_Air\_breathing\_zone}$$

For a perfectly mixed system the air distribution effectiveness is 1. DV has a lower mean age of air in the breathing zone, an indication that supply air is more efficiently distributed to occupants.

When used to describe effectiveness at removing airborne contaminants, it is defined by:

$$\eta = \frac{C_e - C_s}{C_{oz} - C_s}$$

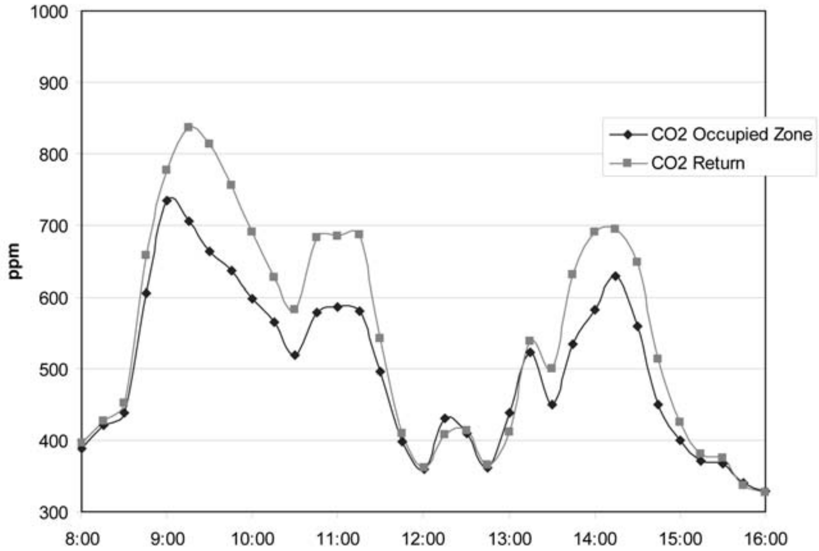
Where C_s, C_e, C_{oz} are the CO_2 concentrations in the supply, at the exhaust, and in the occupied zone, respectively.

A common assumption is a value of 1.0 for mixing systems and 1.2 for DV. This translates to better air quality near the occupants.

Source: Architectural Energy Corporation

Figure 3: Indoor CO2 levels for a DV classroom, Roseville, CA

This monitored data from Sept. 27, 2004, demonstrates that DV achieves a lower CO_2 concentration in the occupied zone than at the return. This improved ventilation effectiveness provides for improved IAQ without increasing the amount of outside air.



Source: Architectural Energy Corporation

climates, where the outdoor temperature is between 55°F and 65°F for a large period of the year. The higher SAT reduces the number of hours when the compressor must run, a direct energy benefit. Also, the thermal stratification from DV results in a higher return air temperature, which extends the economizer range.

Secondly, the higher SAT will allow mechanical cooling equipment to operate at a higher efficiency. Since the SAT is higher, there is a smaller temperature difference between the evaporator outlet and condenser inlet. Thus, less compressor work is required for the same amount of cooling. Finally, DV allows for a reduced capacity of cooling equipment. The air that is exhausted from the space to the outdoors is warmer with DV. This effectively reduces the energy required to “pre-cool” outside ventilation air to the return air temperature. The combination of a more frequent economizer use, greater cooling efficiency and reduced cooling requirement results in cooling energy savings levels that can reach 30–50 percent.

Cooling Capacity Reduction and Demand Savings

With DV, warmer air is exhausted from the space. The warm return air exhausted to the outdoors is replaced by outside air. DV requires less energy to pre-cool the outside air to the return air temperature. As a result, the cooling load on the system is reduced. Another way to show the reduced cooling requirement is to look at the temperature drop across the cooling coil. DV requires a significantly smaller "delta T" across the cooling coil. A smaller tonnage of installed cooling capacity will reduce HVAC capital costs and also provide for demand savings.

Improved Acoustic Performance

DV systems are quieter due to the low air velocities at the diffusers. Also, fans and cooling equipment are typically located remotely, isolated from the interior space. This makes these systems an excellent choice for noise-sensitive areas such as classrooms. When mechanical equipment is located close to interior space, the use of DV may prevent the need for other costly noise abatement measures.

DV helps to meet demanding acoustic requirements for classrooms. The ANSI S12.60 Acoustics Standard and the Collaborative for High Performance Schools (CHPS) both recommend a background noise level of 35 dBA for core learning spaces.

Applications

DV is a good application for facilities where IAQ is a serious concern. Densely occupied spaces with open floor plans, such as classrooms, restaurants, and theaters are excellent applications. DV has also been successfully used in open spaces with high ceilings, such as airport terminals, fitness centers, atria, and casinos.

Schools

Educational facilities, and classrooms in particular, benefit from DV because they require significant amounts of outside air to maintain acceptable IAQ. Since DV has a higher ventilation effectiveness, providing a minimum outside air ventilation of 15 cfm/person will have the equivalent effect of a higher outside air rate from a mixing system (up to 20 cfm/person). Thus, DV can improve IAQ without increasing energy use. DV is most effective when the space has a cooling load. Classrooms have a steady occupancy and in California will have a cooling load for most of the year.

The CHPS Best Practices Design Manual (www.chps.net) contains guidelines for using DV in educational facilities.

Two wall-mounted diffusers provide for a steady supply of cool, fresh air for the typical 960-ft^2 classroom. Analysis performed under the California Energy Commission Public Interest Energy Research (PIER) IEQ Program[3] showed that typical California classrooms require about 1,100 cfm of 65°F supply air at design cooling conditions. DV can also be used effectively in libraries, auditoriums, and gymnasiums.

Restaurants

The air distribution from DV is especially useful in restaurants, another area where IAQ is of the highest importance. The vertical air movement towards the ceiling helps to remove contaminants and prevent the spread of germs.

Theater or Auditorium

This is another open space that is well suited for DV. With stadium seating, air can be supplied from underneath the seats directly to the occupants. DV helps to meet the demanding acoustic requirements of theaters and performing arts centers.

Offices

Office spaces with high ceilings can also benefit from DV. Larger office spaces with open floor plans and partitions are excellent candidates for either underfloor air distribution or DV. Interior offices and conference rooms that have a steady cooling load are also well suited for DV. Perimeter offices or other spaces with low internal heat gains are not as well suited for DV. However, DV can still be used to provide ventilation or cooling, but such spaces may require supplemental heating near exterior windows to maintain comfort.

Industrial Spaces

DV can also provide air quality and energy benefits for industrial spaces with open ceilings, and has been used this way in northern Europe since the 1970s. Industrial processes that generate dust, debris, and other pollutants can adversely affect workers. DV is effective when the contaminants are associated with heat sources, so they can be carried away by buoyancy forces towards the ceiling exhaust. It is not effective in biological laboratories or facilities where contaminants are heavier than air.

Limitations of Displacement Ventilation

Despite its many benefits, there are conditions and applications that are not as well suited for DV. The primary space constraints are ceiling height and the wall space required for the diffusers. DV is also not an efficient method of heating, although heating can be provided through the low-velocity diffusers in many cases.

Ceiling Height

A minimum ceiling height of 9 ft is recommended for DV. High ceilings are necessary to allow internal heat gains and contaminants to be effectively carried to the upper portion of the room. Higher ceilings of 10–12 ft will enhance these benefits of thermal stratification.

Design Cooling Loads

Previous studies have suggested that DV can provide for good comfort under only moderate cooling loads. The studies recommend the use of supplemental cooling, such as chilled ceiling panels, for design cooling loads in excess of 8–10 Btu/h-ft^2. Recent research by ASHRAE and PIER program[4] has shown that DV can provide for effective cooling and good comfort for spaces with cooling loads as high as 25 Btu/h-ft^2. Even greater cooling loads can be handled with the use of higher ceilings. For higher loads, a large diffuser area is required to supply sufficient air volumes while maintaining a low discharge velocity.

Heating with DV

DV provides benefits of comfort, air quality, and energy efficiency during the cooling season. It is most effective when the space has either a cooling load or neutral air requirement. By definition, DV is not well designed for heating. The warm supply air, if supplied from the diffuser at a very low velocity, will tend to rise towards the ceiling exhaust before it can effectively heat the space. (Overhead ventilation systems with a ceiling supply of very warm air and a ceiling return can also have low air distribution effectiveness in heating.[5]) When significant heating is required during occupied periods, a supplemental heating system is the preferred method of heating.

Design Methods and Considerations

Thermal Comfort

DV provides cool supply air in close proximity to the occupants. With the resulting temperature gradient and airflow patterns, special design criteria must be met to ensure good thermal comfort. The SAT must be warm enough and the air velocity low enough to eliminate the possibility of cold drafts at foot level. For most applications, the supply air temperature should be maintained above 62°F; for classrooms with young children, a 65°F minimum is recommended. Low air velocities are a design feature of displacement diffusers, so drafts will not occur if the diffusers have been properly specified and the minimum SAT is maintained.

A maximum temperature gradient in the occupied space is also important in ensuring comfort. ASHRAE Standard 55-2004 recommends a maximum temperature difference between head and foot level of 3.6°F for seated occupants and 5.4°F for standing occupants. This precludes the direct use of cold supply air from typical direct expansion air-conditioning units for DV. If colder supply air, such as 55°F air provided by typical DX units, were discharged low in the space, this would create uncomfortably cool temperatures near the floor.

The temperature gradient in the occupied zone is an important design consideration. There is an optimum airflow that results in a temperature gradient that just meets this comfort threshold. If the airflow is too low, a cooler SAT will be needed to provide sufficient cooling, and the resulting temperature gradient will cause discomfort. If the airflow is too high, there will be less stratification, reducing the energy benefits.

Load Calculations and System Sizing

Any procedure for determining required supply conditions and for sizing HVAC system must start with the fact that the room is

A key comfort design criterion with DV is the maximum temperature gradient in the occupied zone. The occupied zone is defined as the region of the room between foot level (4 in.) and head level (about 42 in.) of the seated occupant.

A temperature difference no more than 3.6°F between head and foot level for seated occupants and 5.4°F between head and foot level of standing occupants is recommended for good thermal comfort.

For mixing ventilation, load calculations are performed for the entire space. For DV, a load calculation is performed for the occupied zone.

not at a uniform temperature. A simple room energy balance will not work. Any sizing procedure must have a means for determining the fraction of heat gains that remain in the occupied portion of the room. The remaining heat gain is transferred to the unoccupied upper portion of the room.

Rough Calculations

As a first-order approximation, for a space with a ceiling height of 9–10 ft, the return air temperature can be assumed to be about 5°F warmer than the air temperature at the thermostat. Although this is a crude approximation, it can provide a first estimate at determining the required design airflow in cooling and the required system capacity. The use of higher ceilings (above 10 ft) that allow for greater displacement of internal loads will result in a higher return air temperature. Spaces with relatively low ceilings (9 ft or less) and high cooling loads will have a return air temperature that is closer to the room temperature.

Through ASHRAE Research Project 949, researchers have examined the application of displacement ventilation in detail, and the resulting guidebook, System Performance Evaluation and Design Guidelines for Displacement Ventilation, provides a wealth of both theoretical and practical information for the designer.

Detailed Load Calculations

Several studies have derived modeling procedures for estimating the required supply airflow from a breakdown of cooling loads and internal heat gains. A recent ASHRAE research project (Chen, Glicksman 2003) resulted in a DV guideline that includes a simple calculation procedure. Empirical coefficients for weighting the effects of lighting, envelope, and occupant and equipment loads on the occupied space were developed from a large set of computational fluid dynamics (CFD) simulations, validated by laboratory testing. Whereas the conventional load calculation estimates the load on the entire space, the DV calculation estimates the load to the occupied zone. An energy balance on the "occupied zone" —defined as the region between 4 in. and about 42 in. for seated occupants—is used to determine the required supply airflow.

Table 2 shows a load calculation for a Sacramento classroom using the ASHRAE design guideline. At summer design conditions of 105°F dry-bulb and 71°F wet-bulb, the room has a space sensible cooling load of 17.2 kBtu/h and space latent load of 4.5 kBtu/h.

Table 2: Mixing vs. displacement load comparison for a hypothetical Sacramento classroom

Although DV requires a slightly higher airflow at design conditions, the sensible load on the coil is reduced. The cooling setpoint is 74°F in both cases.

	Overhead Mixing Air Distribution	**Displacement Ventilation**
Step 1. Itemize Loads—Estimate the load to the occupied zone for DV.		
	Space Load	**Occupied Zone Load**
Occupants and Equipment	8,300 Btu/h	x 0.295 = 2,449 Btu/h
Lighting	3,300 Btu/h	x 0.132 = 436 Btu/h
Envelope	5,600 Btu/h	x 0.195 = 1,092 Btu/h
Space Load Subtotal (kBtu/h)	17,200 Btu/h	N/A
Occupied Zone Load Subtotal	N/A	3,977 Btu/h
Step 2. Airflow Calculation—Supply airflow is calculated from an energy balance on the occupied zone. The Delta T of 3.6 meets the ASHRAE Standard 55 comfort criterion. A space cooling setpoint of 74°F is assumed.		
Delta T	74–55 = 19°F	3.6°F (between 4” and 43” height)
Supply Airflow	825 cfm	1005 cfm
Step 3. Determine SAT and RAT—DV supply temperature is determined from ASHRAE design guidelines. Return air temperature is determined from an energy balance on the entire space.		
SAT	55°F	65.8°F
RAT	74°F	81.3°F
Room “Delta T”	19°F	15.5°F
Step 4. Calculate System Load—Once the supply airflow, SAT, and RAT are known, the required cooling capacity is determined in a similar manner to a mixing ventilation system.		
Outside Air	450 cfm 105°F DB	450 cfm 105°F DB
Return Air	375 cfm 74°F DB	555 cfm 81.3°F DB
Mixed Air (entering coil condition)	825 cfm 90.9°F DB	1,005 cfm 91.9°F DB
Supply air (leaving coil)	825 cfm 55°F	1,005 cfm 65.8°F
Sensible Cooling Capacity (Coil Load)	**32,580 kBtu/h**	**28,870 kBtu/h**
Latent Occupant Load	4,500 Btu/h	4,500 Btu/h
Outside Air Latent Load	–880 Btu/h	–4,500 Btu/h
Latent Cooling Capacity	3,620 Btu/h	0 Btu/h
Total Cooling Capacity	**36,200 Btu/h**	**28,870 Btu/h**
Indoor Relative Humidity	**50%**	**56.6%**

Source: Architectural Energy Corporation

The required supply air temperature and supply airflow were estimated from ASHRAE design guidelines.[6] In this example, the design supply airflow is 22 percent higher with DV. Once the SAT and supply airflow are known, the return air temperature is determined from a room energy balance. The load on the cooling coil consists of the space load and ventilation load. A portion of the warm air at the ceiling is returned to the coil, and the remainder is exhausted to the outdoors. The air that is exhausted is replaced by outside air. With DV, warmer air is exhausted from the space. This effectively lowers the energy required to "pre-cool" the outside air to the return air temperature, resulting in a lower sensible cooling capacity.[7]

With conventional air distribution systems, as the supply air is cooled to 55°F, moisture is removed from the supply air as well, to maintain indoor space humidity levels. For California climates, dehumidification will not normally occur if the supply air is only cooled to a 65°F dry-bulb temperature. The DV system will have a much lower latent load on the coil than a mixing system, at the expense of a slightly higher indoor humidity level. In dry, inland California climates, the moisture content of the outdoor air is lower than that of the indoor air throughout the year. Thus, providing outside ventilation air will also serve to dehumidify the space. For coastal climates, the humidity of the outdoor air will occasionally be higher than indoor design levels. A portion of the supply air may need to be cooled to below its dewpoint to provide for dehumidification.

The ASHRAE design guideline used in this classroom example is an appropriate calculation method for determining design supply airflow requirements for DV applications in classrooms, offices and workshops with normal ceiling heights (9–13 ft). For large spaces with high ceilings, such as theaters and atria, CFD analysis is recommended to determine supply conditions that will remove the space load and maintain comfort.

Energy Simulations

As part of the design process, the design team will want to estimate the energy savings from DV. Commonly used energy simulation programs such as DOE-2 assume a fully mixed air space for load and energy calculations. While procedures exist, programs that assume a fully mixed air space are fundamentally unable to model airflow and heat transfer that occur in unmixed spaces.

The energy simulation model should account for the thermal stratification that occurs in the space with DV. This is required to estimate the return air temperature and required supply airflow, and for proper system sizing and estimates of required fan energy. Simply defining a higher supply air temperature will not work, although this is a common "work-around." One option is to model the upper unoccupied space of the room as an unconditioned "plenum," and assign a fraction of the heat gain from internal and lighting loads to the fictitious plenum. A related approach proposed by Addison and Nall (2001) is to use advanced expression capabilities of DOE-2.2, which allow the user to enter parameters as algebraic or logical expressions. The distribution of internal heat gains from lights, occupants, and equipment can be assigned to the occupied zone or the unoccupied zone (modeled as a plenum) by user-defined expressions. Modeling references are provided at the end of this brief for more information.[8]

Energy models for DV must account for thermal stratification in the space to appropriately estimate cooling energy savings. This is especially important for incentive programs such as Savings By Design.

EnergyPlus is an alternative building energy simulation tool that has incorporated procedures for modeling DV. The model characterizes the thermal stratification in the space by determining the average air temperature at three "nodes:" near the floor, in the occupied zone, and in the upper, unoccupied portion of the room. It only requires a single user input, for the fraction of the room heat gains that are transferred via convection to the occupied zone of the space. For classrooms, offices, and spaces with ceiling heights of 9–12 ft, a recommended guideline is to enter this fraction in the EnergyPlus input file as 0.2–0.3. The resulting design airflow calculated by the program is similar to ASHRAE design guideline predictions.

EnergyPlus provides a better estimate of the required airflow in the unmixed air space, and consequently, a more accurate energy prediction, than simulation programs that assume a fully mixed air space. With the additional temperature data, the program also allows for a better evaluation of thermal comfort.

Detailed Airflow Analysis: CFD

CFD is a useful tool for predicting airflow patterns that result from DV. It produces very detailed predictions of air velocity and temperatures for a given set of boundary conditions. However, it is a time-intensive process that requires a sophisticated understanding of the physical phenomena that occur to achieve accurate results. Moreover, CFD analysis models the space for an instant in time; it does not account for transient effects such as motion of occupants on room airflows. Commercial CFD packages also have built-in routines for predicting thermal comfort. CFD is especially useful in specifying displacement diffusers and diffuser layout for large spaces or spaces with complex geometry. However, for small spaces such as classrooms or conference rooms, it is not necessary. Diffuser manufacturers can assist with sizing and specification.

Diffuser Selection and Layout

DV uses diffusers that are specifically designed for the supply of low-velocity supply air. The supply air is discharged from the diffuser at a very low face velocity, typically 50–75 fpm. This requires a significant diffuser area to meet design cooling airflow. Because the supply air is introduced directly to the occupied zone, there are separate performance criteria for this type of diffuser. For overhead ceiling diffusers, performance is characterized by throw and air diffusion performance index (ADPI). These metrics do not apply to DV. A key design criterion for displacement diffusers is the adjacent zone. This is the region near the diffuser where the potential for drafts exist when cool supply air is introduced into the space. Normally this is defined as the area where the local air velocity exceeds 40 fpm. As a general rule, desks and workstations should be located at least 5–6 ft away from column diffusers, to minimize potential for cold drafts at foot level. Manufacturers publish adjacent zone data for a given supply airflow and temperature difference between the supply air and room air (see sidebar).

Another criterion is the noise criteria (NC rating) for the diffusers. DV aids with good acoustic design. A best practice for acoustic design includes sizing diffusers for a combined noise criteria of NC-28 (corresponding to 35 decibels–A scale or dBA) for noise-sensitive areas, such as classrooms, and NC-37 (45 dBA) for other spaces. Manufacturers can assist with selection of diffusers to meet design needs.

There are several architectural options for diffusers and the layout will vary with the application. For a classroom application, two quarter-round diffusers provide for a good air distribution and uniform cooling throughout the space. These are typically surface-mounted against the corners of the interior wall. Supply air can be brought down to the diffusers through concealed ducts, or from a common supply plenum.

Architectural Design Considerations

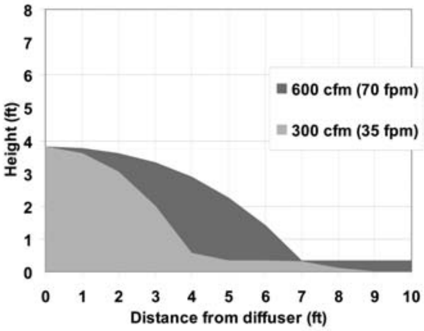
The primary requirement that is unique to DV is the use of high ceilings, to allow for thermal stratification. A minimum 9-ft ceiling is recommended; ceilings of 10 ft or higher will enhance the benefits. Since there may be an opportunity to reduce or eliminate ductwork above the ceiling, the floor-to-floor height for multiple-story structures may remain the same.

Aside from the ceiling height requirement, any buildings designed with efficiency in mind will likely be good candidates for DV. A well insulated building envelope with high performance fenestration and exterior shading for non-north-facing windows will moderate peak cooling loads. DV can be effectively used for spaces with design space cooling loads as high as 25 kBtu/h-ft^2.

DV relies on a vertical, buoyancy-driven air movement from the floor supply towards the ceiling exhaust. A well insulated building

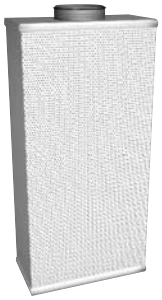
Figure 4: Diffuser criteria: adjacent zone

The adjacent zone is the region near the diffuser where the local air velocity exceeds some specified threshold (typically 40 fpm). This is the area where the potential for draft exists. The figure below shows a reduction in the adjacent zone when the airflow is reduced from 600 cfm to 300 cfm. DV is well suited for VAV control.



Source: Halton Company

Figure 5: Diffuser options



Rectangular

Half-Round 180° Diffuser

Quarter-Round 90° Diffuser

Freestanding 360° Circular Diffuser

envelope is important for proper system operation during winter. Downdrafts from cold exterior walls and windows will oppose the displacement airflow. With a well insulated envelope and high performance windows, DV will work well in the winter when the space has a cooling load.

Diffuser Options

While diffusers for DV take up considerable wall area, there are several diffuser options that can be seamlessly integrated into the space. Installers and occupants often comment on how they appear to be part of the building design.

Some common diffuser options include:

- Corner Diffuser: these are located in the corner of the space. Air is typically supplied to the top of the unit from a concealed duct. This is a common option for classrooms.
- Half-Round 180° Diffuser: typically located along an interior wall, these provide for uniform cooling as the supply air flows out towards the exterior wall.
- Freestanding 360° Circular Diffuser: these are located in the interior of large, open spaces. They allow for large airflows without the presence of draft. Air can be supplied from the top or from an underfloor plenum.
- Recessed Rectangular Diffuser: diffusers can be recessed into the wall to minimize impact on floor space.
- Plenum Diffuser: a rectangular diffuser may be integrated underneath casework, or used underneath stairways in theaters and auditoriums.

The warm, contaminated air can be returned at any location in the space, at or near the ceiling. If it is convenient to do so, locating the return near the exterior wall will promote efficient removal of envelope and solar heat gains through fenestration.

HVAC Design Considerations

Using Direct-expansion Units

While DV can provide for good IAQ and reduced energy use, there are specific design requirements for the heating, ventilation, and air-conditioning (HVAC) system. When the space has a cooling load, the system must be able to provide a steady supply air temperature near 65°F, under varying load conditions. Typically, small packaged rooftop DX units used in light commercial applications do not meet these requirements. To be effective, the system needs multiple cooling stages (preferably 3 or more) for adequate SAT control. At low load conditions, the system might require the use of hot gas bypass on the first cooling stage, to prevent the supply air from getting too cold. However, hot gas bypass is not energy efficient. A system that can control the SAT to within 3°F–4°F of the SAT setpoint will work well with DV.

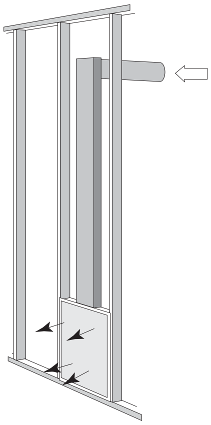
Larger packaged units of a 20-ton cooling capacity or greater have more cooling stages and more sophisticated control options than

Figure 6: Displacement ventilation in a classroom

The low-velocity displacement diffuser helps meet demanding acoustic requirements for K-12 classrooms.

Source: Halton Company

Figure 5: Diffuser options (continued)



Recessed Diffuser

Plenum Feed

Source: Halton Company, Price HVAC

single-zone, constant-volume packaged units. A single, larger packaged system that serves multiple spaces, with VAV terminal units for individual space control, is a good system choice for DV.

Central Plant Design

A central plant works well with DV. With the higher supply air temperature, the chilled water setpoint can be increased from 45°F to around 55°F. As a result, the chiller can run at a higher coefficient of performance (COP). The reduction in required capacity provides an opportunity to downsize the chiller, resulting in lower total HVAC costs.

The required supply air conditions can be achieved with standard equipment. A typical control would vary the supply air temperature setpoint from 62°F–68°F in cooling. The SAT is controlled by varying the flow of chilled water to the air handler coil. The chilled water temperature setpoint can vary (from 52°F–58°F, for instance) based on the zone with the highest cooling demand. Air handlers supply the cool, conditioned air to VAV terminal units for zone temperature control. With the higher supply temperature, the requirement for reheat is reduced and may even be eliminated.

Some facility designs may specify DV for some spaces but require overhead air distribution in others. Combining ventilation types can be a challenge. For efficient operation, spaces served by overhead air distribution should be served by separate air handlers. Serving both spaces by the same chiller plant does not take advantage of a higher cooling efficiency through the use of a higher chilled water setpoint temperature. The chilled water temperature must be set lower to meet the needs of the overhead air distribution system, decreasing chiller efficiency. The lower chilled water setpoint will also increase the number of hours at which the plant must operate. An alternative would be to provide a separate dedicated system to serve spaces that use overhead air distribution.

Heating Options

DV uses a steady supply of cool air to remove heat and contaminants from the space. To be effective at maintaining comfort and IAQ, it relies on a vertical air movement from the floor supply towards the ceiling exhaust. The low-velocity diffusers designed for DV are not as effective in heating. In heating, the goal is a well mixed air space. To allow for mixing of the warm supply air with the cooler room air, a higher air velocity is required. Some displacement diffuser manufacturers are addressing this issue by designing the diffusers with a variable aperture. When the room calls for heating, the opening area reduces, to increase the discharge air velocity from the diffuser. This higher air velocity promotes mixing of the air, resulting in more effective heating of the space.

When providing heating through the low-velocity diffusers, a moderate SAT (around 80°F–85°F) is recommended due to the proximity of the diffusers to the occupants. The use of low-output heating and a high airflow will moderate the supply air temperature. For more temperate climates, the use of low-velocity diffusers allows for adequate comfort in heating. Heating needs during occupied hours will be minimized, or even eliminated, with a morning warm-up control strategy that heats the room to the occupied setpoint prior to occupancy. Once the space is occupied, internal gains from occupants, lighting, and equipment will offset envelope losses to the outdoors.

For some climates, or for perimeter spaces with low internal heat gains, heating through low-velocity diffusers cannot maintain comfort during the winter. Cold downdrafts from windows will oppose the rising thermal plumes. For climates where the winter design dry-bulb temperature is 15°F or lower, a separate perimeter heating system is recommended. If a separate heating system is desired, heating can be provided via radiators at perimeter walls or by radiant floor heating. The cool supply air will be heated as it spreads across the warmed floor.

Humidity Control

High indoor humidity is not a concern for dry, inland California climates. Throughout the year, the outdoor humidity levels are well below design indoor humidity levels. Thus, outside ventilation air will serve to offset latent loads from occupants. For southern California coastal climates, however, outdoor humidity levels are above indoor design levels for significant portions of the year. At times, the HVAC system would need to remove moisture from the entering air to maintain suitable indoor conditions. Even mild, humid conditions that occasionally occur in coastal climates can create a problem with indoor humidity.

Conventional cooling equipment provides dehumidification by using 55°F supply air to cool the space. The use of 65°F supply air, typical of DV, will not provide for significant dehumidification. Some of the supply air must be cooled to below its dewpoint temperature. Unless coupled with an HVAC design that provides for dehumidification without reheat, this requirement for a lower supply air temperature will reduce the cooling energy benefits of DV. There are several ways to address this problem without requiring wasteful reheat energy.

Return air bypass. When the outside air requires dehumidification, a bypass damper can direct up to 100 percent of the return air to bypass the cooling coil. Since less air passes over the cooling coil, this lowers the air temperature leaving the coil. The dehumidified air off the coil (near 55°F) is mixed with the bypassed warmer return air to achieve the 65°F supply air temperature.

Mixed air bypass. Face-and-bypass dampers allow the entering air (a mix of outside air and return air) to bypass the cooling coil. While this is a low-cost option, it does not dehumidify as effectively during humid outdoor conditions, since some of the outside air also bypasses the coil.

Condenser heat recovery. A "run-around" coil can capture heat rejected from the condenser and warm the supply air downstream of the cooling coil.

Heat recovery or total energy recovery. Outside air is preconditioned by the exhaust air stream, removing both heat and moisture with total energy recovery. With this option, 100 percent outside air can be used.

For coastal climates, the specification of a differential enthalpy economizer will help to maintain space humidity levels during mild, humid outdoor conditions. Maintaining enthalpy-based sensors can be a challenge, however.

Each of these options provides dehumidification without reducing the SAT setpoint. Humidity control options are more practical with larger packaged systems or with large air handling units and a central plant. Humidity control is more difficult with smaller, constant-volume packaged units.

Control Options

With DV, the space temperature can be controlled by varying the supply air temperature, the supply air volume, or both. VAV systems will allow for fan energy savings at part-load conditions. Control strategies that allow for variation of both the supply air volume and SAT have the greatest potential for energy savings. A 65°F SAT is often only needed at design cooling conditions. SAT reset will maximize the potential for free cooling.

Because of the temperature stratification, the thermostat location is an important design consideration. It should be located at a height approximately equal to head level of seated occupants (42 in.). The thermostat should be located outside of the adjacent zone of the diffuser, to avoid cool drafts at foot level. A location at least 6 ft from the nearest diffuser will work well for space temperature control.

Economizer Operation

With the higher SAT, DV extends the period of free cooling. However, it does require a low ambient temperature lockout on the economizer, which closes the outside air damper to the minimum position when the outside air falls below a certain

DV Control Fundamentals

- Space temperature can be controlled by varying supply air volume, SAT, or both air volume and temperature.
- Control the SAT to within 3°F–4°F of the SAT setpoint to maintain comfort.
- Specify SAT reset to maximize the potential for free cooling.
- Implement a low ambient temperature lockout on the economizer.
- Specify a morning warm-up sequence to minimize heating needs during occupied hours.

temperature (i.e., 60°F). When the outside air temperature is below this point, a mix of outside air and return air must be used to avoid discharging cold air into the space. A differential dry-bulb lockout with return air temperature will provide for efficient operation in dry, inland climates. An enthalpy-based economizer is a good option in more humid, coastal climates.

For most climates, the outside air damper should be reset to the minimum position, to maintain energy efficiency during hot outdoor conditions. However, keep in mind that the return air temperature (RAT) is typically about 5°F warmer than the air temperature at the thermostat. In some temperate coastal climates with low humidity levels, 100 percent outside air could be used for cooling, without incurring a large energy penalty.

Energy Benefits and System Costs

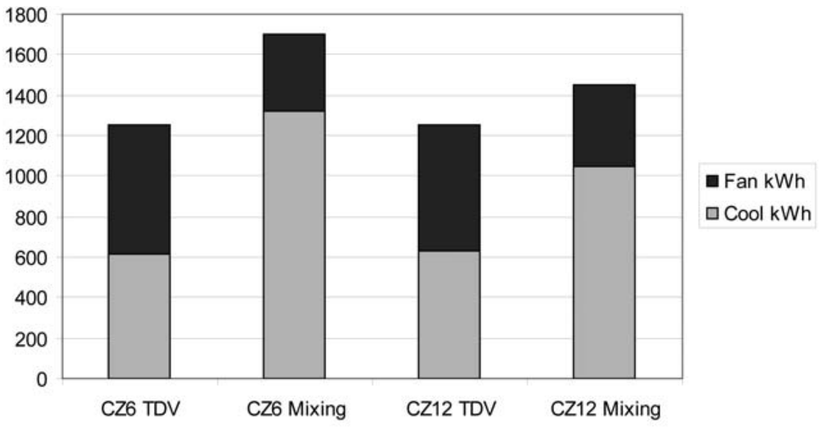
Energy Savings

Since DV has not been used extensively in the United States, there are little data on energy use. Several studies have predicted the energy use of DV for different climates and have made comparisons to traditional ventilation systems. DV will normally require a slightly higher design supply airflow, which may result in higher annual fan energy. However, the cooling energy savings will normally outweigh any increase in fan energy, resulting in a net savings. **Figure 7** shows an annual energy prediction for a single classroom using DV. EnergyPlus was used to model the DV system. A packaged DX unit with variable air volume control with the same cooling efficiency was assumed in both cases.

Coastal climates will benefit most from the extended range of economizer operation. The simulation shows an annual cooling energy savings of 54 percent for the Los Angeles classroom, and nearly 40 percent for the Sacramento classroom. Despite the higher airflow requirement, a net energy savings is realized with DV. Applications in coastal, temperate areas will benefit most from the extended economizer range possible with DV’s higher

Figure 7: EnergyPlus classroom energy use comparison

EnergyPlus annual energy prediction for a single classroom with packaged VAV cooling. Despite higher fan energy, a 54% reduc-tion in cooling energy for Climate Zone 6 (Los Angeles) and a 40% reduction for Climate Zone 12 (Sacramento) results in net energy savings.



Source: Architectural Energy Corporation

supply air temperature. Applications in hot, inland climates will have more modest cooling energy savings.

The potential energy savings for DV depends upon a number of factors. Climate, load profiles, building design, and HVAC system design will have a large impact on the results.

System Costs

First cost is often mentioned as a possible barrier to the use of DV. The diffusers will carry an additional cost premium of about $1–$2/ft^2 of floor area. This cost may be partially offset by simplification of ductwork. In some cases, the cost of the air handling units may be slightly higher with DV. However, if packaged DX equipment is used, DV may require custom features—multiple compressors and additional controls and sensors to control the supply air temperature. Thus, for designs that specify packaged cooling, DV may carry an additional cost. The total HVAC system cost may be less for DV if a central plant is used. Since the total required cooling capacity is reduced, there is an opportunity to downsize the chiller. The net result is a total initial HVAC cost that is slightly higher than a comparable overhead mixing system.

DV is more easily achieved with a central plant. Initial installed costs are typically higher for a central plant than for packaged rooftop HVAC units. However, central cooling systems typically have lower operating and maintenance costs, which can result in lower lifecycle costs.

DV does not trigger any special architectural requirements that will affect construction costs. In most cases, the floor-to-floor height for typical construction will work. Good building envelope design measures, such as high-performance fenestration and exterior shading for exposed glazing, will help to maintain comfort throughout the year.

Table 3: HVAC system cost comparison for an eight-classroom wing

A cost comparison for a hypothetical eight-classroom building located in southern California shows a slight cost increase for DV. Incremental costs for diffusers and controls are partially offset by a reduction in cooling capacity. Costs are representative and do not reflect specific market or project conditions.

	Overhead Mixing Ventilation		Displacement Ventilation	
	Packaged VAV Rooftop Unit	Air-Cooled Chiller & Boiler	Packaged VAV Rooftop Unit	Air-Cooled Chiller & Boiler
Cooling Load	27.2 tons	27.2 tons	24 tons	24 tons
System Selection	30 tons	30 tons	25 tons	25 tons
Cooling Eqp. Cost	$85,500	$80,000	$75,000	$70,000
Boiler	---	$20,000	N/A	$20,000
Controls	N/A (std.)	N/A (std.)	$10,000	$10,000
VAV Terminal Units	$40,000	---	$40,000	---
Fan Coil Units	---	$64,000	---	$64,000
Diffusers and Ductwork	$24,000	$24,000	$32,000	$32,000
Total Installed Cost	**$149,500**	**$188,000**	**$157,000**	**$196,000**
Cost/ft²	**$19.50**	**$24.50**	**$20.40**	**$25.50**

Source: Architectural Energy Corporation

Examples

With its potential for reduced energy use, good IAQ, and acoustics, DV has been used in schools, libraries, and auditoriums in the United States.

Blue Valley North High School

Blue Valley North High School in Overland Park, Kansas, implemented DV in the media center and classrooms during an HVAC system retrofit. The additional 11,000 cfm of outside air required to bring the school up to code would have required an additional 40 tons of cooling with conventional ventilation. With the installation of more efficient lighting, a demand-controlled ventilation scheme, and DV, only 30 tons of cooling was required. The combined effect of these energy-efficient HVAC design measures resulted in a 20 percent annual electricity savings. (**Figure 8**)

Cardiff-by-the-Sea Branch Library

Cardiff-by-the-Sea Branch Library in San Diego County uses DV to provide cooling and ventilation for the 6,242-ft^2 space. Air is delivered at 62°F–67°F to large column diffusers (**Figure 9**). A 17.7-ton VAV cooling unit uses an enthalpy-integrated economizer to take advantage of the large number of hours of free cooling in this climate. Ten diffusers provide for uniform cooling throughout the space.

Figure 8: School Example: Blue Valley North High School, Overland Park, Kansas

DV was integrated into classrooms, the library, and media center. The use of DV resulted in a drop in indoor CO2 levels below the ASHRAE Standard 62 recommended limit.

Source: Larson Binkley, Inc.

Figure 9: Library Example: Cardiff-by-the-Sea Branch Library, California

DV was selected in part because of the location's tremendous potential for free cooling. The project qualified for the Savings By Design incentive program. In the Cardiff-by-the-Sea branch library, the large duct at right provides supply air near floor level. Warm air is exhausted via the diffuser on the wall above the circulation desk.

Photo by Frank Domin. Courtesy of Manuel Oncina Architects, Inc.

FOR MORE INFORMATION

Manufacturers

Halton Company, Trox, and Price manufacture low-velocity diffusers for DV applications.

Trade Associations

ASHRAE has recently published design guidelines for DV. This comprehensive guidebook (Chen, et al. 2003) is a culmination of ASHRAE Research Project 949.

REHVA (Federation of European Heating and Air-Conditioning Associations) has published a guidebook (Skistad 2002) for DV in non-industrial premises. The book contains detailed graphical depictions of air flow patterns and applications for a classroom, office, restaurant, conference room, and auditorium.

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Notes

1 In this design brief, the acronym "DV" is used to refer to displacement ventilation. In literature it is often referred to as thermal displacement ventilation (TDV). Here, DV is used to avoid confusion with time-dependent valuation used in the 2005 Title 24 Standards.

2 The Center for the Built Environment at University of California-Berkeley has conducted extensive research and experimental testing of underfloor air distribution (UFAD). www.cbe.berkeley.edu/underfloorair/

3 Supply air requirements for California K–12 classrooms were determined by CFD analysis performed under a PIER Research program (See note 5). The CFD analysis was validated by full-scale measurements and later confirmed through monitoring of a demonstration classroom in the Sacramento area.

4 See ASHRAE's 2003 publication "System Performance Evaluation and Design Guidelines for Displacement Ventilation," and PIER Research Program 500-03-003, Advanced HVAC Systems for Improving Indoor Environmental Quality and Energy Performance of California K–12 Schools, www.archenergy.com/ieq-k12

5 ASHRAE 62.1-2004 assumes a heating ventilation efficiency of 0.7 for displacement ventilation and 0.8 for overhead mixing air distribution when the SAT is at least 15°F warmer than the room air.

6 The design procedure is included in the ASHRAE publication "System Performance Evaluation and Design Guidelines for Displacement Ventilation" (Chen 2003).

7 This example assumes the same outside air ventilation rate for both the mixing and displacement system. If one assumes that the DV system requires less outside air, due to a higher ventilation effectiveness, the cooling capacity would be further reduced.

8 See Addison and Nall (2001) and Chen and Griffith (2002) in the For More Information section for options on modeling displacement ventilation with energy simulation programs.

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