Summary
Displacement ventilation (DV) is an alternate air distribution method for commercial and industrial spaces. 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 displace heat and contaminants towards the ceiling exhaust. First costs of diffusers are offset by simplified ductwork and the possibility for a downsized chiller, often resulting in a lower total system cost.

Displacement ventilation provides improved IAQ, cooling energy savings, and better acoustics for high performance buildings.
**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 at a relatively high velocity from ceiling outlets. 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 entrainment of room air into 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. Table 1 summarizes distribution system differences.

<table>
<thead>
<tr>
<th>Table 1: Air Distribution System Comparison.</th>
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<tbody>
<tr>
<td><strong>Overhead (Mixing)</strong></td>
</tr>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>Diffusers located in the ceiling deliver 55°F air at velocity of 400–700 ft per minute. Objective is a well-mixed airspace.</td>
</tr>
<tr>
<td><strong>Supply Conditions</strong></td>
</tr>
<tr>
<td>Nominally 55°F in cooling.</td>
</tr>
<tr>
<td><strong>Architectural Requirements</strong></td>
</tr>
<tr>
<td>Space above ceiling for ductwork and ceiling diffusers.</td>
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<tr>
<td><strong>Thermal comfort</strong></td>
</tr>
<tr>
<td>Even temperatures throughout the space in cooling with proper design.</td>
</tr>
<tr>
<td><strong>Ventilation effectiveness</strong></td>
</tr>
<tr>
<td>FAIR—Supply air mixes with room air to dilute contaminants.</td>
</tr>
<tr>
<td><strong>Acoustic performance</strong></td>
</tr>
<tr>
<td>Diffusers can be a noise source if the air velocity is too high.</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
</tr>
<tr>
<td>Any</td>
</tr>
<tr>
<td><strong>Lower Wall (Displacement)</strong></td>
</tr>
<tr>
<td><strong>Description</strong></td>
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<tr>
<td>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.</td>
</tr>
<tr>
<td><strong>Supply Conditions</strong></td>
</tr>
<tr>
<td>Typically 63°F–68°F air in cooling.</td>
</tr>
<tr>
<td><strong>Architectural Requirements</strong></td>
</tr>
<tr>
<td>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.</td>
</tr>
<tr>
<td><strong>Thermal comfort</strong></td>
</tr>
<tr>
<td>Very good thermal comfort in cooling with proper design. Some potential for drafts near the diffusers.</td>
</tr>
<tr>
<td><strong>Ventilation effectiveness</strong></td>
</tr>
<tr>
<td>VERY GOOD—Supply air is delivered directly to occupants, and contaminants are displaced to the upper unoccupied zone.</td>
</tr>
<tr>
<td><strong>Acoustic performance</strong></td>
</tr>
<tr>
<td>Quieter due to lower air velocity at the diffusers.</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
</tr>
<tr>
<td>Offices or any space with open floor plans.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Underfloor Air Distribution (Mixing/Displacement)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>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.</td>
</tr>
<tr>
<td><strong>Supply Conditions</strong></td>
</tr>
<tr>
<td>Typically 60°F–64°F in cooling. Some temperature rise will occur in the underfloor plenum.</td>
</tr>
<tr>
<td><strong>Architectural Requirements</strong></td>
</tr>
<tr>
<td>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.</td>
</tr>
<tr>
<td><strong>Thermal comfort</strong></td>
</tr>
<tr>
<td>Good thermal comfort with proper airflow. Potential for individual temperature control.</td>
</tr>
<tr>
<td><strong>Ventilation effectiveness</strong></td>
</tr>
<tr>
<td>GOOD—Better than overhead distribution, but some mixing occurs in the occupied zone.</td>
</tr>
<tr>
<td><strong>Acoustic performance</strong></td>
</tr>
<tr>
<td>Also quieter due to low velocity.</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
</tr>
<tr>
<td>Offices or any space with open floor plans.</td>
</tr>
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</table>

Source: Architectural Energy Corporation
Why Use Displacement Ventilation?
Outside air ventilation is a means of treating indoor air by diluting airborne contaminants. Within the past few decades, building design professionals have increasingly recognized the importance of providing fresh air to improve indoor air quality (IAQ). Studies have revealed problems with IAQ in commercial buildings, particularly in academic environments. HVAC systems are designed to introduce sufficient outside air to maintain an acceptable air quality standard. For densely occupied spaces, outside air ventilation significantly increases system cooling loads during hot outdoor conditions. Increasing the amount of outside air will improve air quality, but will also increase cooling energy costs.

DV addresses the problem of IAQ without increasing energy use. In fact, it will usually reduce cooling costs. It provides distinct benefits of improved IAQ, lower cooling energy use, and better acoustics. However, to fully realize these benefits, there are both architectural and HVAC system requirements. These design details are discussed in subsequent sections.

How Is It Achieved?
The best cooling source for a displacement ventilation 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. 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 can be used as an alternative to a chilled water system. For example, a packaged rooftop variable air volume (VAV) system serving multiple spaces should be able to provide the necessary supply air temperature control.

During low cooling loads, modulating hot gas bypass may
be needed to raise the supply air temperature. However, this negates many of the energy benefits. Evaporative cooling is also a potential source because it typically produces higher air temperatures than a DX system.

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 a very low air velocity, the diffusers do 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. And, there is 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. The primary benefits are improved IAQ, reduced energy use, and improved acoustic performance. There also may be an opportunity to reduce the system cooling capacity.

**Improved Indoor Air Quality**

Since air is supplied near the floor of the space, ventilation air is provided directly to the occupants. 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. This tends to improve IAQ without increasing the ventilation load on the HVAC system. 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. ASHRAE Standard 62.1-2010, which refers to this as air distribution effectiveness, assumes a DV effectiveness of 1.2. This means that a space served by DV requires 20 percent less outside air than a
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:

$$\eta = \frac{\text{Mean Age Air exhaust}}{\text{Mean Age Air breathing zone}}$$

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 $C_s$, $C_e$, and $C_{oz}$ 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.

![Figure 2: Ventilation effectiveness](source)

Figure 2: Ventilation effectiveness

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![Figure 3: Indoor CO2 Levels for A DV Classroom, Roseville, CA](source)

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 requiring a greater amount of outside air.

This benefit has been demonstrated in K-12 classroom applications throughout the United States (see Figure 3).

The vertical flow pattern towards the ceiling exhaust promotes removal of heat-borne contaminants and will result in an improved air quality in the occupied zone. Ventilation effectiveness is also used to quantify the effectiveness of the ventilation system at removing air-borne contaminants. Carbon dioxide is an indicator of the effectiveness of ventilation in diluting air-borne 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 percent–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, or even lower than, that required for the mixing system. Moreover, when VAV control is included and conditions allow for free cooling, a lower supply air volume can be used with DV. Since the room air is stratified, there is a greater temperature difference between the outside supply air temperature and the return air.

Cooling energy savings with DV has many contributing factors. With DV, warmer air is exhausted from the ceiling return, and the supply air is only cooled to 65°F. The net result is that the cooling load on the system is reduced (see Table 2). Secondly, there are a greater number of hours when free cooling can be used. Also, since increasing the supply air temperature will raise the evaporator temperature, the system will operate at a higher coefficient of performance (COP). The actual energy savings
depends greatly on the system design, climate and load profile, but cooling energy savings levels can reach 30 percent–50 percent.

**Cooling Capacity Reduction and Demand Savings**

DV uses a much higher supply air temperature than overhead air delivery systems. This contributes to a lower required system cooling capacity. (This is illustrated in the design example in the Table 2.) 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. This makes them an excellent choice for noise-sensitive areas such as classrooms. In a field study of side-by-side classrooms served by displacement ventilation and traditional overhead ventilation, the classroom with DV had interior noise levels of 4dB or greater lower than the noise levels in the classroom served by overhead ventilation levels, when weighted on an A-weighted scale (weighted towards human speech). When mechanical equipment is located close to interior space, the use of DV may prevent the need for costly noise abatement measures.

**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, gymnasiums and 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 the Title 24 minimum outside air 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.

Two wall-mounted diffusers provide for a steady supply of cool, fresh air for the typical 960 ft² classroom. Analysis performed under the California Energy Commission Public Interest Energy Research (PIER) Indoor Environmental Quality (IEQ) Program showed that typical California classrooms require about 1100 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 air quality 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**

Open space areas such as theaters and auditoriums are 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 underfloor air distribution. DV is well-suited for interior offices and conference rooms that have a steady cooling load. Perimeter offices 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 that they can be carried away by buoyancy forces towards the ceiling exhaust. It is not as effective in biological laboratories and 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. These include spaces with low ceilings, buildings in hot and humid climates, and buildings in heat-dominated climates. DV could still be used in these situations, but the energy and air quality benefits are reduced.

**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 displaced into the upper portion of the room. Ceiling heights of 10 ft –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∙ft². Research by ASHRAE and the California Energy Commission PIER Program has shown that displacement ventilation can provide for effective cooling and good comfort for spaces with cooling loads as high as 25 Btu/h∙ft². Even larger cooling loads can be handled with the use of higher ceilings. However, a large diffuser area is required to supply sufficient air volumes while maintaining a low discharge velocity.

**Dehumidification**

The primary energy benefit lies in the fact that the supply air need only be cooled to 65°F. For most California climates, buildings generally do not require dehumidification of the outside air. However, in some coastal climates, or for spaces with high
latent loads, the outside supply air may have to be cooled well below 65°F to provide dehumidification. 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. Humidity control options are discussed in the HVAC Design section.

**Heating Climates**

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. When significant heating is required during occupied periods, a supplemental heating system is the preferred method of heating. However, this will increase system costs.

In most California climates, and for facilities that have a steady occupancy, the heating load is low and can be provided by the low-velocity displacement diffusers. In colder climates, such as Lake Tahoe, a separate perimeter heating system is recommended to maintain comfort throughout the winter.

**Design Methods and Considerations**

During the design phase, it is important to consider thermal comfort and the impact on the load and system sizing. Also, DV Design Do's and Don'ts are summarized in the table on the next page.

**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 supply air temperature (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...
A maximum temperature gradient in the occupied space is also important in ensuring comfort. ASHRAE Standard 55-2010 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 displacement ventilation. 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. Computational fluid dynamic (CFD) models can provide detailed predictions of temperature fields and airflows. Some commercial CFD packages also provide comfort predictions as simulation output.
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 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.

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. An ASHRAE research project (Chen, Glicksman 2003) resulted in a displacement ventilation guideline that includes a simple calculation procedure. Empirical weighting coefficients for weighting the effects of lighting, envelope, and occupant and equipment loads on the occupied space were developed from a large set of 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.

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

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.
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>
<thead>
<tr>
<th>Table 2: Mixing versus Displacement Load Comparison for A Hypothetical Sacramento Classroom</th>
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<tbody>
<tr>
<td>Although DV requires a slightly higher airflow at design conditions, the sensible load on the coil is reduced.</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Overhead Mixing Air Distribution</th>
<th>Displacement Ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1. Itemize loads</strong>—Estimate the load to the occupied zone for displacement ventilation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space Load</td>
<td>Occupied Zone Load</td>
<td></td>
</tr>
<tr>
<td>Occupants and Equipment</td>
<td>8300 Btu/h</td>
<td>x 0.295 = 2449 Btu/h</td>
</tr>
<tr>
<td>Lighting</td>
<td>3300 Btu/h</td>
<td>x 0.132 = 436 Btu/h</td>
</tr>
<tr>
<td>Envelope</td>
<td>5600 Btu/h</td>
<td>x 0.195 = 1092 Btu/h</td>
</tr>
<tr>
<td><strong>Space Load Subtotal (kBTU/h)</strong></td>
<td>17,200 Btu/h</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Occupied Zone Load Subtotal</strong></td>
<td>N/A</td>
<td>3,977 Btu/h</td>
</tr>
</tbody>
</table>

| **Step 2. Airflow Calculation**—Supply airflow is calculated from an energy balance on the occupied zone. The ΔT of 3.6 meets the ASHRAE Standard 55 comfort criterion. A space cooling setpoint of 74°F is assumed. |
| **ΔT** | 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. |
| **Room Setpoint** | 74 °F | 74 °F |
| **SAT** | 55 °F | 65.8 °F |
| **RAT** | 74 °F | 81.3 °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 | 450 cfm |
| | 105 °F DB | 105 °F DB |
| **Return air** | 375 cfm | 375 cfm |
| | 74 °F DB | 74 °F DB |
| **Mixed air (entering coil condition)** | 825 cfm | 825 cfm |
| | 90.9°F DB | 90.9°F DB |
| **Supply air (leaving coil)** | 825 cfm | 825 cfm |
| | 55 °F | 55 °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
As indicated in Table 2, not all heat sources will have the same impact in a space conditioned by DV. Much of the convective heat gain from overhead lighting will remain in the upper, unconditioned portion of the space. A portion of the heat gain from occupants and equipment will be carried by the “thermal plumes” towards the ceiling as well.

The required supply air temperature and supply airflow were estimated from ASHRAE design guidelines. In this case, 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. Some of the warm air at the ceiling return is exhausted to the outdoors, and for most applications, a portion of the air is returned to the cooling coil. Despite the higher airflow requirement for DV, Table 2 shows a slight reduction in required system sensible cooling capacity. Because the warm outside air need only be cooled to 65°F, the required sensible cooling capacity will be slightly lower with DV.

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 the dewpoint to provide for dehumidification. (Humidity control options are discussed in the HVAC Design Considerations section.)

Much of the research on DV has concentrated on determining the “split” of loads between the lower occupied zone and the
upper unoccupied zone. Accurately estimating this split is 
evenential in sizing equipment and estimating annual cooling 
energy requirements. 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 ft to 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. Hourly energy simulation 
programs, such as DOE-2, are used to estimate annual energy 
use. Commonly used energy simulation programs 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 
occurs 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, 
for proper system sizing and estimates of required fan energy. 
Simply defining a higher supply air temperature will not work. 
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 (such as ceiling height) as algebraic or 
logical expressions. The distribution of internal heat gains from 
lights, occupants, and equipment can be assigned to the occupied 
subzone or the unoccupied subzone (modeled as a plenum) by 
user-defined expressions. Solar gain to the two subzones can be 
managed by setting the fenestration dimensions and heat gain
coefficients appropriately. This allows for a high degree of user control, but requires a sophisticated level of understanding of and experience with the building energy simulation program.

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 9ft to 12ft, a recommended guideline is to enter this fraction in the EnergyPlus input file as 0.2 to 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 very time-intensive process that requires a sophisticated understanding of the physical phenomena that occur to achieve accurate results. 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

Selection Criteria
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 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.

Typical Layout
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-ft².

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

Diffusers for DV require considerable wall space. 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 promotes efficient removal of envelope and solar heat gains through fenestration.

**HVAC Design Considerations**

**Using Direct-expansion Units**

While DV can provide improved IAQ and reduced energy use, there are specific design requirements for the 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. Some small packaged rooftop direct expansion (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) or variable-capacity compressors for adequate SAT control. Hot gas bypass can be used at low load conditions to control supply air temperature, but is not recommended because of its inefficiencies.

Packaged single-zone DX units, which use variable-capacity compressors or DigitalScroll™ compressors, provide good capacity modulation at low load conditions. This results in a steady supply air temperature that is necessary for occupant
comfort. A unit with multiple compressors and cooling stages will also provide some control of supply air temperature, but will not work as well as units that provide continuous capacity modulation.

Larger packaged units with 20-ton cooling capacity or greater have more cooling stages and more sophisticated control options than 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 higher allowed supply air temperature reduces ventilation loads, and this slight reduction in required capacity may provide 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 can vary the supply air temperature setpoint from 62°F to 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 to 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 displacement ventilation for some spaces but require overhead air distribution in others. Combining ventilation types is a special 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 can be inefficient. The chilled water temperature must be set lower to meet the needs of the overhead air distribution system, decreasing cooling 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 of the diffuser 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. If the low air velocity typical of displacement diffusers were used with heated air, some of the supply air may short-circuit towards the ceiling return before it has a chance to heat the space.

When providing heat through the low-velocity diffusers, a moderate SAT (around 80°F to 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 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 will 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. 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. Dampers control the fraction of return air that bypasses the coil. As the humidity in the space decreases, the amount of return air directed to the cooling coil can increase, to increase the leaving air temperature and capture energy savings.

**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. However, maintaining enthalpy-based sensors can be a challenge.

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 systems.
units and a central plant. Humidity control is more difficult with smaller, constant-volume packaged units. The HVAC system should include multiple cooling stages. This has several benefits. The variable capacity allows for a steady 65°F supply temperature as the space load varies. Also, the use of multiple cooling stages will reduce equipment cycling, resulting in better humidity control at part-load conditions.

**Control Options**

With DV, the space temperature can be controlled by varying the supply air temperature, the supply air volume, or both. Variable air volume (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 supply air temperature have the greatest potential for energy savings, and are the preferred means of control. A 65°F SAT is often only needed at design cooling conditions. SAT reset will maximize the potential for free cooling.

The recommended control strategy varies the supply air volume as the primary means of control. If the supply air volume is at the minimum and the space is still overcooled (below the setpoint), the supply air temperature is increased. If the supply air volume is at the maximum setting and the space is still undercooled (above the setpoint), the SAT is decreased, with a minimum setpoint of 63°F to 65°F.

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 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.

For most climates, the outside air damper should be reset to the minimum position, to maintain energy efficiency during hot outdoor conditions. However, the return air temperature (RAT) is typically 3-5°F warmer than the air temperature at the thermostat. In spaces with high ceilings above 12 feet, the return temperature can be more than 5 degrees above the space temperature. In some temperate coastal climates with low humidity levels, 100 percent outside air could be used for cooling, without incurring a large energy penalty. However, economizer dampers should be closed to the minimum position when the space requires heating.

**Energy Benefits and System Costs**

**Energy Savings**

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 increased 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. Table 3 presents a comparison of annual cooling energy use for DV and conventional mixing ventilation system for a typical classroom built to 2005 Title 24 standards. The classroom has a space sensible load of 15.4 kBtu/h and a design space temperature of 74°F. The cooling energy savings for Sacramento, San Francisco, and Los Angeles is 38 percent, 67 percent, and 64 percent, respectively.

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. The ceiling height will impact energy use by affecting the required supply airflow. A high ceiling will promote energy benefits due to stratification. Climate also has an impact — applications in coastal, temperate areas will benefit most from the extended economizer range possible with DV’s higher supply air temperature. Applications in hot, inland climates will have more modest cooling energy savings. DV can also provide demand savings by reducing the cooling capacity requirement.

**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/
ft² 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 TDV. System designs that specify packaged single zone DX systems may require a slight premium for systems that include capacity modulation. However, with the new Title 24 Standards that require single zone VAV systems down to 75 kBtu/h by January 2014 and to 65 kBtu/h by January, 2016, this price increment is not expected to persist. The total HVAC system cost may be less for DV if a central plant is used. Since the total required cooling capacity is reduced, the opportunity exists to downsize the chiller.

For designs that specify a central plant, displacement ventilation will not carry an additional cost. However, if packaged DX equipment is used, displacement ventilation 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 a slight additional cost. The requirement for a separate perimeter heating system may

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**Table 3: Chiller Annual Energy Consumption Comparison: DV versus Mixing Ventilation**

Coastal climates can take advantage of the greater number of hours with free cooling using DV. This analysis assumes weekday operating hours of 7AM to 3PM, 1% cooling design conditions, and uses TMY hourly weather data to estimate annual energy consumption. Both ventilation cases assume a chiller coefficient of performance (COP) of 3.0.

<table>
<thead>
<tr>
<th>SAT, °F</th>
<th>SACRAMENTO</th>
<th>SAN FRANCISCO</th>
<th>LOS ANGELES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DV</td>
<td>Mixing with return</td>
<td>DV</td>
</tr>
<tr>
<td>All OA</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Return</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Airflow, cfm</td>
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<td>1099</td>
<td>1099</td>
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<tr>
<td>Return air temp, °F</td>
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<td>78.1</td>
<td>74</td>
</tr>
<tr>
<td>Outside Airflow, cfm</td>
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<td>315</td>
</tr>
<tr>
<td>Cooling Capacity, ton</td>
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<td>2</td>
<td>2.1</td>
</tr>
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<td>Cooling hours</td>
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<td>1088</td>
<td>220</td>
</tr>
<tr>
<td>Annual cooling energy, MWh</td>
<td>1</td>
<td>0.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Source: Architectural Energy Corporation
also increase total HVAC costs. However, a significant reduction in operating costs should result in lower life-cycle costs for DV systems.

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.

**Examples**

With its potential for reduced energy use, improved 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 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-ft2 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. While the DV system requires different controls than a standard system, cooling is provided by standard HVAC components.
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. The photos below show the column-style diffusers used throughout the school.

Source: Larson Binkley, Inc.

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

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. The large duct at right provides supply air near floor level. Warm air is exhausted via the diffuser on the upper wall on the right side of the image.

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

Manufacturers
The following companies manufacture low-velocity diffusers for displacement ventilation applications.
Halton Company - www.haltoncompany.com
Trox® Technik – www.troxtechnik.com
Price Industries – www.price-hvac.com

Trade Associations
ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers) has recently published design guidelines for DV. This comprehensive guidebook (Chen, et. al. 2003) is a culmination of ASHRAE Research Project 949. www.ashrae.org

REHVA (Federation of European Heating and Air-Conditioning Associations) has published a guidebook (Skistad ed. 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.

Publications


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 2013 Title 24 Standards.

2. The Center for the Built Environment at U.C. Berkeley has conducted extensive research and experimental testing of underfloor air distribution (UFAD). For more information, see http://cbe.berkeley.edu/underfloorair/Default.htm.


4. 2006 EDR Case Study. The field study showed a significant reduction in interior classroom noise levels with displacement ventilation, making it easier to meet the requirements of the ANSI classroom acoustics standard (ANSI-S12.60-2010). http://energydesignresources.com/resources/publications/case-studies/case-studies-displacement-ventilation-in-classrooms.aspx

5. Supply air requirements for California K-12 classrooms were determined by CFD analysis performed under a PIER Research program (See note 6). The CFD analysis was validated by full-scale measurements and later confirmed through monitoring of a demonstration classroom in the Sacramento area.


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

8. 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 higher ventilation effectiveness, the cooling capacity would be further reduced.

9. The simulation assumed a school year from August 15 through June 15. The model uses an input of 0.3 as the fraction of heat gains convected to the occupied space. The supply air temperatures for the overhead mixing case and displacement ventilation case were 55°F and 65°F, respectively.
Energy Design Resources provides information and design tools to architects, engineers, lighting designers, and building owners and developers. Our goal is to make it easier for designers to create energy efficient new nonresidential buildings in California. Energy Design Resources is funded by California utility customers and administered by Pacific Gas and Electric Company, San Diego Gas and Electric, Southern California Edison, and Southern California Gas Company under the auspices of the California Public Utilities Commission. To learn more about Energy Design Resources, please visit our Web site at www.energydesignresources.com.

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