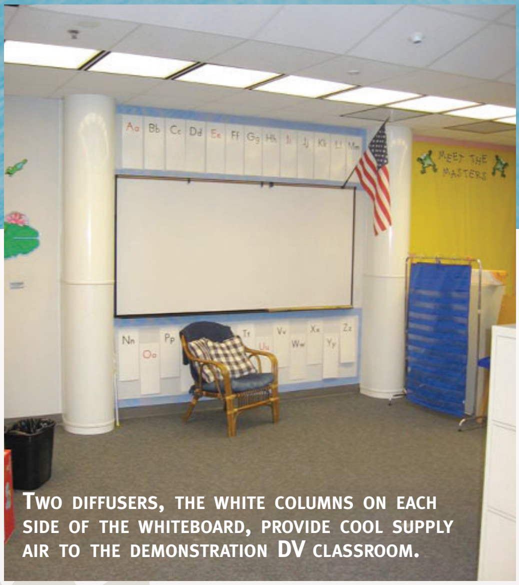


Two diffusers, the white columns on each side of the whiteboard, provide cool supply air to the demonstration DV classroom.

The DV classroom demonstration featured a customized rooftop HVAC unit.

Displacement Ventilation in Classrooms

Performance Monitoring Objectives for Classroom Demonstration

- Evaluate thermal comfort, indoor air quality (IAQ), and acoustics
- Monitor indoor conditions and air conditioning systems continuously for six months
- Compare energy use of displacement system to traditional system
- Survey teachers on comfort and IAQ
- Provide results for calibration with empirical models of displacement ventilation

Introduction

Displacement ventilation (DV) is an air distribution system designed to simultaneously improve indoor air quality and reduce energy use. Cool, rather than cold supply air is provided through low sidewall diffusers directly to occupants. The cool air, at about 65°F rather than 55°F, falls to the floor due to gravity and spreads across the floor. When the cool supply air comes into contact with occupants and equipment, the heat from these sources causes the air to warm and rise. This creates a vertical air movement, driving heat towards the ceiling exhaust. Room contaminants are carried away towards the ceiling exhaust, resulting in improved air quality near the occupants.

Schools, restaurants, theaters and auditoriums, atria, other open spaces with high ceilings, and spaces where air quality is a concern are excellent applications.

Overcoming Market Barriers through Technology Demonstration

As part of a recent California Energy Commission Public Interest Energy Research (PIER) project on displacement ventilation, a market barriers study was conducted, to reveal both real and perceived barriers to displacement ventilation. Among those inexperienced with the technology, the major obstacles are anticipated increases in system costs and the scarcity of DV projects in California. Many engineers and architects want to see working examples before they commit to an unfamiliar technology. Displacement ventilation has been used in many schools in the Northeast and Midwest, but has seen little use in California.

Displacement ventilation is a particularly good fit for California schools. The moderate climate presents an excellent opportunity to take advantage of a greater period of economizer operation with the more moderate supply air temperature (SAT) of the DV system, leading directly to cooling energy savings. Also, since heating requirements are minimal once the classroom is occupied, the system can typically be deployed without the need for a supplemental perimeter heating system.

Despite the many advantages of displacement ventilation, there is some reluctance towards its application. Common questions include:

- What ceiling height is required?
- Will the students' feet get cold?
- Won't the movement from occupants affect the thermal stratification in the room?
- Will the use of a higher supply air temperature maintain the desired indoor humidity levels?
- Will there be a big increase in fan energy requirements, offsetting cooling energy savings?

These are some of the questions that the researchers hoped to answer in the DV demonstration classroom.

DV Classroom Demonstration

The displacement ventilation monitoring study, co-funded by PIER and San Diego Gas & Electric, compared two classrooms, side by side. At Kinoshita Elementary in San Juan Capistrano, California, a classroom with a standard four-ton packaged rooftop unit and overhead mixing ventilation serves as the control for the study. The control classroom is adjacent to the displacement ventilation classrooom. The DV classroom uses a heating, ventilation, and air-conditioning (HVAC) system that is specifically designed to provide the supply air conditions required for displacement ventilation. The monitoring study is designed to estimate the impact of displacement ventilation on energy use.

The primary monitoring objective is to compare the thermal comfort, indoor air quality, and HVAC energy use of the displacement ventilation classroom against the control classroom. Thermal comfort is verified through air temperature measurements and surface temperature spot measurements. Measurements of carbon dixoide levels verify ventilation effectiveness, the primary IAQ benefit with DV. HVAC electricity use was also monitored over a six-month period. System performance data verified proper system operation and control of supply air temperature. All monitored data was collected at one-minute intervals. Finally, teacher feedback was obtained from biweekly comfort surveys.

While heating can be supplied through low-velocity diffusers, heating requirements for many southern California climates are low and are primarily provided during morning warm-up prior to occupancy. For heating design considerations and other HVAC design details, consult the EDR Design Brief on Displacement Ventilation. A related EDR Design Brief with valuable information is Underfloor Air Distribution.

www.energydesignresources.com

OTHER RESOURCES

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

Results from the Displacement Ventilation work under the PIER Indoor Environmental Quality Project are shown at the below web site. Information includes the full results from the field demonstration described in this case study and a market barriers study. Design criteria and product information from the study are also available.

www.archenergy.com/ieq-k12

Monitoring Details

With displacement ventilation, the vertical air pattern that enhances the removal of heat and contaminants towards the ceiling exhaust results in thermal stratification, with the coolest air near the floor. Temperature measurements at different heights were taken to verify that the resulting stratification falls within comfort limits defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55. For each classroom, platinum RTDs (resistance temperature detectors with accuracy to 0.36°F) recorded temperatures at heights of 4", 40", 66" and 90" above the floor, at three different locations (see Figure 1). Outside air temperature (OAT) and return air temperature (RAT) were also measured. Relative humidity (RH) was measured in the occupied zone and at the exhaust with Vaisala 50U sensors, which have accuracy to three percent. RH measurements verified that acceptable humidity levels were maintained with the DV system.

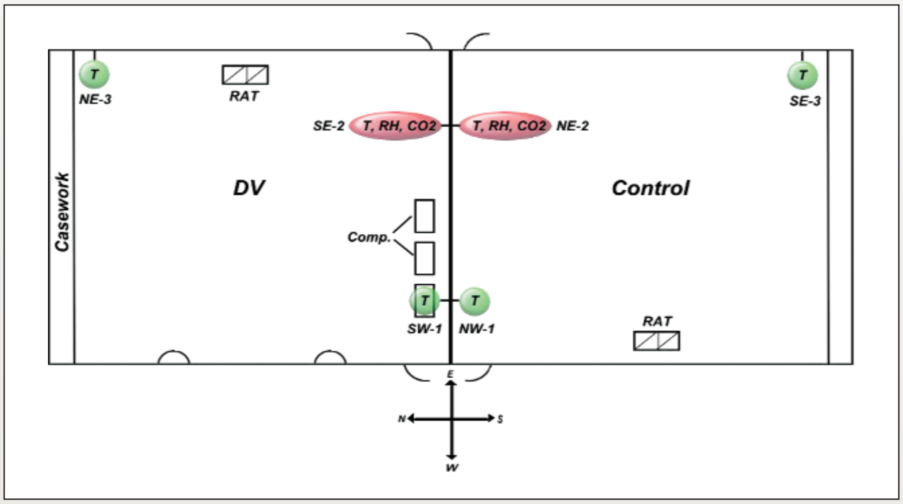


FIGURE 1.

Schematic Layout of indoor monitoring equipment.

Carbon dioxide (CO_2) levels in the occupied zone, at the exhaust, and outdoors were measured with Vaisala non-dispersive infrared transducers to an accuracy of ±70 ppm (parts per million) at 2000 ppm full scale. Displacement ventilation is expected to improve ventilation effectiveness. A CO_2 level in the occupied zone that is consistently lower than the concentration at the return would verify good ventilation effectiveness. In comparison, mixing systems are expected to have steady CO_2 concentrations throughout the space.

A four-ton single-zone packaged rooftop unit serves each classroom. Electricity use of each unit was monitored with Magnelab five amp current transducers and WNA-3D-480P Watt-hour transducers. Both classrooms have both exterior and interior doors. Open doors will provide a secondary source of ventilation, impacting the ability to evaluate HVAC ventilation through CO_2 measurements. Open doors can also affect cooling loads and space temperatures. For this reason, door status was monitored with Amseco AMS-39 contact switches.

HVAC Design Detail – Capacity Control

One barrier that was clearly identified in the research project is the dominance of packaged direct-expansion (DX) rooftop units in the California K-12 market. Why is this an obstacle? Displacement ventilation relies on a steady supply of 65°F air to efficiently remove heat and contaminants and maintain comfort. Small packaged HVAC systems deliver a constant volume of cooler (typically 55°F) supply air, and cycle on and off to meet space loads. The cooler supply temperature and temperature fluctuations would compromise comfort in a DV application.

Chilled water systems are a good fit with displacement ventilation. The hydronic control valve that supplies the air handler can modulate capacity to achieve the needed supply temperature. However, central plants are not always practical with school designs, and often carry a higher installation cost. For displacement ventilation, a packaged system that provides capacity control is needed.

The DV demonstration classroom is conditioned by a HVAC unit that is specially designed for tight control of supply air temperature. The system features the Copeland DigitalScroll™ compressor technology, which allows for a reduction in cooling output down to as low as 10 percent of full capacity. This virtually eliminates the on-off cycling that commonly occurs with small packaged systems. The unit also incorporates a variable-speed drive for the supply fan to provide fan energy savings at part-load conditions.

The Results

Thermal Comfort

Space temperatures were monitored to assess thermal comfort provided by the DV system. Figure 2 shows air temperatures at four different heights in the DV classroom. A steady pattern of stratification is achieved between floor level (4") and head level (66"). The level of stratification conforms to the ASHRAE 55 comfort criteria for unmixed spaces. Figure 3 shows

DV helps meet demanding acoustic requirements for classrooms. The ANSI (American National Standards Institute) S12.60 Acoustic Standard and the CHPS guidelines both recommend a background noise level of 35 dBA (decibels) for core learning spaces. This is difficult to achieve when packaged rooftop units are located above classrooms.

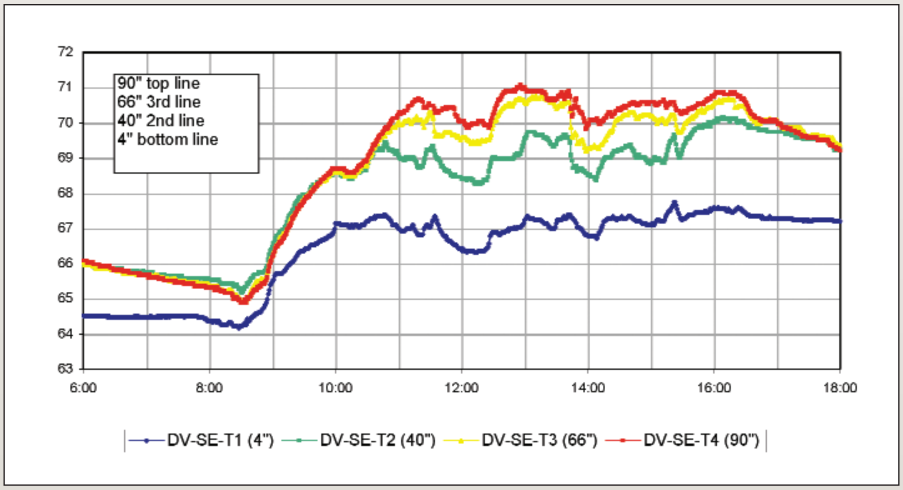
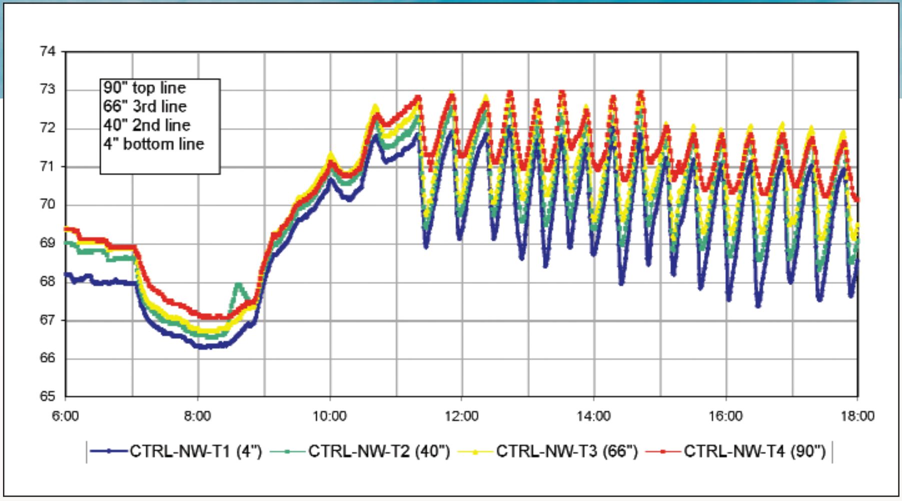


FIGURE 2.

Monitoring results from the displacement ventilation classroom show a consistent pattern of stratification between the floor and head level of occupants. Measurements were taken at four heights: 4", 40", 66", and 90" above the floor.

FIGURE 3.

Compressor cycling from the single-stage constant volume system results in frequent temperature fluctuations in the control classroom, which uses an overhead mixing ventilation system.

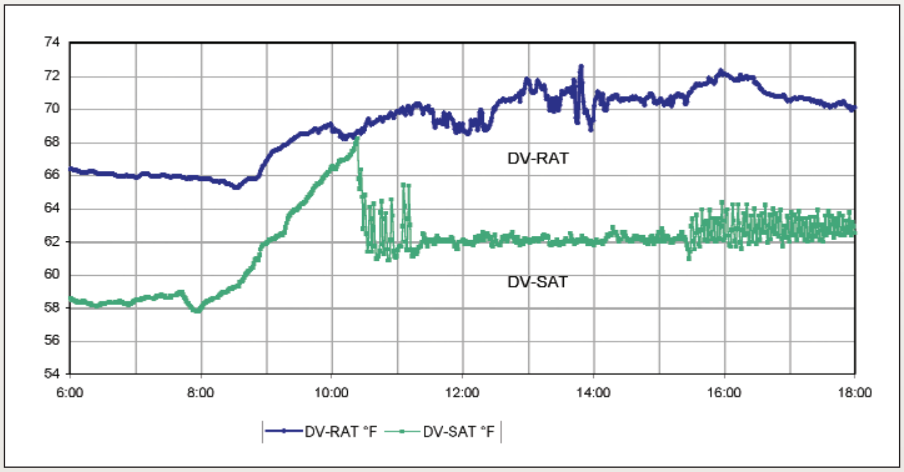


a plot of air temperatures at different heights in the control classroom, which uses overhead mixing ventilation. The frequent cycling that occurs with a single-stage, constant-volume unit results in frequent fluctuations in room temperatures.

The displacement ventilation design allows the cooling capacity to be varied continuously to meet the space load. As a result, the supply air temperature is controlled closely to the SAT setpoint (see Figure 4). This allows for good space temperature control with the DV system.

FIGURE 4.

DV supply and return temperatures, September. 15, 2005. A steady supply of 62-65°F air provides excellent thermal comfort.



With the use of a higher supply air temperature, some engineers have been concerned that displacement ventilation may not provide sufficient dehumidification in some cases. The results from the demonstration indicate that the RH is maintained to acceptable levels in the DV classroom (see Figure 5). While the conventional unit provides additional dehumidification, it is not necessary in this instance. Moreover, the humidity levels vary widely in the conventional classroom as the unit cycles on and off to meet space sensible loads.

Small packaged HVAC units that have a single stage of cooling are designed to meet space sensible loads. During low load conditions, the compressor cycles frequently to meet the space load. The result is poor humidity control. While the HVAC unit for the DV classroom uses a higher SAT, the capacity control allows for steady cooling at part-load conditions. When the SAT is cooled below the dewpoint, this results in improved humidity control.

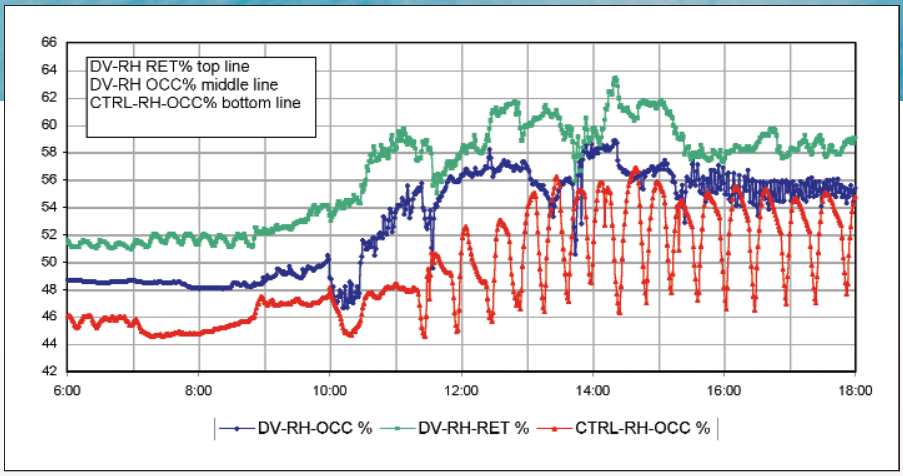


FIGURE 5.

Relative Humidity, September 15, 2005. While the RH in the DV classroom is slightly higher than the RH in the control classroom, it remains within acceptable limits.

Indoor Environmental Quality

The primary IAQ benefit of the displacement ventilation system is improved ventilation effectiveness. In the DV classroom, the CO_2 concentration is consistently lower in the occupied zone than in the return (Figure 6). As a result, the outside air is delivered more effectively to the occupants.

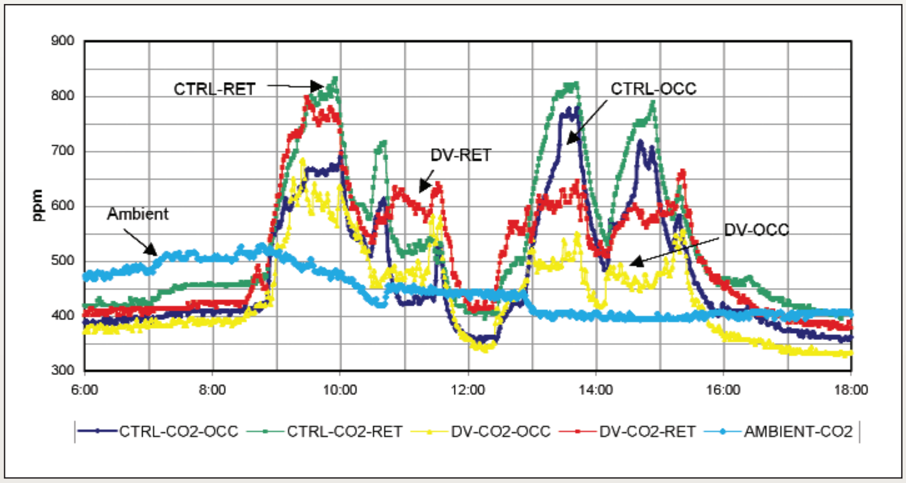


FIGURE 6.

The CO_2 concentration in the occupied zone of the displacement ventilation classroom is consistently lower than the concentration at the return, a sign of good ventilation effectiveness.

Another noticeable benefit of DV is an improvement in acoustics. Spot measurements of background noise levels were 40-44 dBA for the DV classroom (with the fan at maximum speed) and 48-50 dBA for the control classroom. As a result, teachers are less likely to turn HVAC fans off due to noise, which impacts both comfort and air quality.

Energy Comparison: Tuning into Savings

Electricity and gas use of the HVAC units were measured at one-minute intervals. Figure 7 shows measured electricity use of the two HVAC units on September 15, 2005. The variable-speed drive allows for energy savings at part-load conditions, as evident before 10:30AM on this day. The variable-capacity compressor allows the unit to match the capacity to the load. This reduces both peak demand and reduces compressor cycling, resulting in improved comfort.

HVAC electricity use was monitored during the fall 2005 semester. Initially, energy monitoring results did not show a reduction in HVAC electricity use in the DV classroom.

FIGURE 7.

HVAC electricity use for DV unit and control HVAC unit for September 15, 2005.

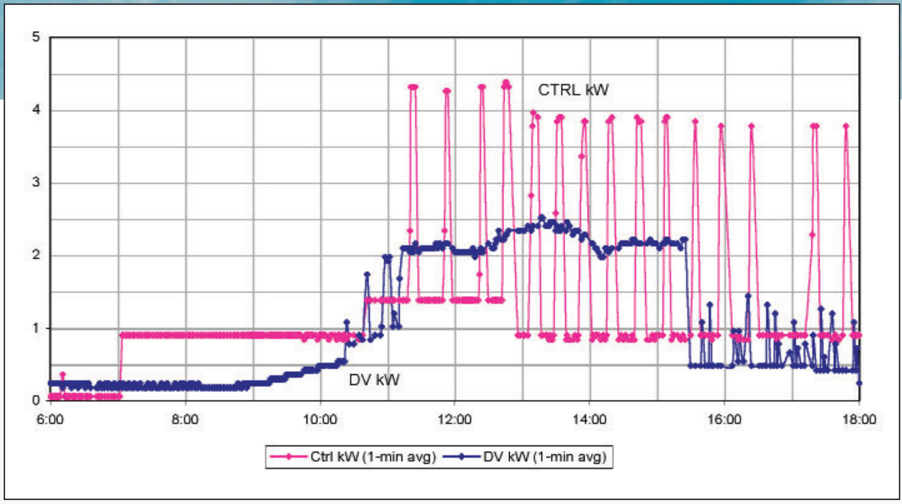


TABLE 1.

Control adjustments to the DV HVAC unit resulted in a sharp drop in electricity use, resulting in net energy savings.

Period	Control Elec Use	DV Elec Use	Savings
Aug-Oct 2005	19.6 kWh/day	22.4 kWh/day	(14%)
Nov 2005	10.3 kWh/day	6.3 kWh/day	39%
Totals	567.6 kWh	499.4 kWh	12%

However, an investigation of the data for the two classrooms showed that the DV classroom was being maintained to a cooler average temperature. Moreover, the HVAC system's economizer settings were not optimally set for DV. After configuration changes were made to the DV unit, the energy monitoring results showed a significant energy savings.

The principal factors behind the energy savings with displacement ventilation are the extended economizer operating range and the reduction in cooling load in the occupied zone. Additional savings are available through the use of a variable-speed drive for supply fan control. The monitoring data showed that for the demonstration classroom, a fan speed of 50-60 percent is sufficient to condition the space. Since fan power varies with the cube of fan speed, this provides a large reduction in fan energy. Operational savings also should make DV an appealing investment.

Other Considerations

Teacher feedback (see sidebar) also has been positive in the displacement ventilation classroom. The teachers in the two classrooms were given surveys on the acoustics, indoor air quality, and thermal comfort. The teacher in the displacement classroom gave the DV system slightly higher marks for both acoustics and thermal comfort.

The primary incremental cost of the HVAC system for DV is the incremental cost of the variable-speed drive. The cost of the diffusers will likely be partially offset by the simplification of ductwork.

Since installation of the displacement ventilation system in her classroom, Kinoshita Elementary Schoolteacher Stephanie Daniel isn't the only one to notice a difference. "It's like walking in fresh air, like being outside all the time," she says. "During open house, all the other teachers wanted to know when they're getting one in their classrooms."

Conclusions

The demonstration classroom at Kinoshita Elementary confirmed that displacement ventilation provides good thermal comfort for classrooms with normal ceiling heights (9 feet). The DV system did not create problems with cold drafts at the floor. The system provides a consistent thermal stratification in the space and good ventilation effectiveness. The effects of occupant activity and the opening of doors and windows did limit the amount of stratification achieved in practice. However, the system provides a remarkable improvement in acoustics.

The energy savings potential for this demonstration was not realized during the initial phase of the project. Control setting modifications and tuning dramatically improved system performance. With VAV systems, where air volume is the primary means of space temperature control, compressor operation is not directly tied to space temperature (and cooling requirements). Under such a control strategy, control tuning and verification are critical to ensuring system performance.

Displacement ventilation can be achieved today using a variety of HVAC system designs. Large, off-the-shelf HVAC units that have multiple cooling stages are compatible with the DV system design requirements. The principal design requirement is a steady supply of 65°F air. The customized HVAC unit used in this study proved to be effective in meeting the design requirements, and is unique in its ability to provide single-zone, VAV control for a single classroom. Further development of additional innovative HVAC design options for displacement ventilation will likely offer increased opportunities for energy savings.

Displacement ventilation has shown to provide effective ventilation and excellent thermal comfort for California classrooms. Acoustic benefits alone are a compelling reason to use DV. Energy savings are significant, especially when the HVAC system includes variable-speed drive and variable-air-volume (VAV) control for fan energy savings.

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