Displacement Ventilation in Action: Performance Monitoring of Demonstration Classrooms

Charles Eley and John Arent, Architectural Energy Corporation
Bradley Meister, California Energy Commission

ABSTRACT

Displacement ventilation (DV) can provide better acoustics, improved indoor air quality, and reduced energy use for schools and other buildings. Recent research has used CFD simulation to determine supply air requirements and predict thermal comfort. However, there is a scarcity of performance data from these systems in practice. This paper presents recent research results from a Public Interest Energy Research (PIER) funded study of the technology and its application to K-12 schools. Two demonstration classrooms were continuously monitored over a six-month period to evaluate DV's impact on thermal comfort, indoor air quality and energy use.

Each of the displacement ventilation classrooms was compared to a control classroom that used a conventional packaged rooftop unit and overhead mixing air distribution. The demonstration and control classrooms were instrumented to record room temperature, carbon dioxide concentrations, relative humidity levels, and HVAC system electricity use. Temperatures were recorded at four different heights for each of three different locations to verify that thermal stratification in the space conforms to ASHRAE standards for thermal comfort.

The monitoring data shows a consistent pattern of thermal stratification in the displacement classrooms. The displacement classrooms also have a lower CO_2 concentration in the occupied zone than at the ceiling return, a sign of good ventilation effectiveness. Feedback from teacher surveys of thermal comfort, indoor air quality and acoustics is testament to the benefits of displacement ventilation. The results of the demonstration classrooms will help bridge the gap between theory and practice and will be a catalyst for market adoption.

Demonstration Sites and HVAC Solutions

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 higher supply air temperature 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. Normally, heat gains from occupants, equipment and lighting will offset losses to the outdoors when the classrooms are occupied. When heating is required, heat can be provided at a moderate supply air temperature of 80-90°F with acceptable results. Despite the many advantages of DV, there is some resistance towards its application. Those unfamiliar with the technology are concerned about potential issues with cold drafts at floor level, indoor humidity levels, and the effects of occupant movement and other real-world conditions on room air distribution and indoor air quality. The PIER-funded study is designed to address these questions.

Two existing schools were selected for the technology demonstration, one in a hot inland climate and one in a temperate coastal climate. The DV system was installed at Coyote Ridge Elementary in Roseville, CA in the summer of 2004 and monitored for a period of one year. DV was installed at Kinoshita Elementary in San Juan Capistrano, CA in April 2005 and was monitored through the spring of 2006. Both demonstrations were retrofits of existing classrooms that had overhead mixing ventilation from four ceiling diffusers. Both classrooms feature nine foot suspended ceilings, with a skylight in the center of the classroom. Each classroom was monitored along with an adjacent control classroom that uses a conventional packaged rooftop direct-expansion (DX) unit and an overhead mixing ventilation system.

DV relies upon the steady supply of 65°F air, delivered low in the space, to exhaust room contaminants and provide space cooling and ventilation. Standard overhead mixing systems typically use cooler, 55°F supply air, to condition the space. The HVAC solutions at both sites were designed to meet DV air delivery requirements.

The DV classroom at Coyote Ridge used a chilled water system and variable air volume air handler to maintain required supply conditions. With this system, the supply air volume is varied as the primary means of space temperature control, from a minimum of 450 cfm to a maximum of 1100 cfm. The supply air temperature (SAT) is controlled by varying the flow of chilled water through a cooling coil using a hydronic control valve. The supply air temperature setpoint is 65°F. Reset of supply air temperature occurs if the heating setpoint cannot be maintained at minimum air flow or if the cooling setpoint cannot be maintained at maximum airflow. Heating and cooling space setpoints for both the DV and mixing Coyote Ridge classrooms were 70°F and 76°F, respectively. For Capistrano, the heating and cooling space setpoints were 68°F and 74°F. For the DV classrooms, the thermostat was located at head level of the seated students on an interior wall .The primary objective of the first demonstration was to verify the supply air conditions required for DV to maintain comfort, and to verify that the system provides good thermal comfort and indoor air quality (IAQ) throughout the school year.

The second demonstration at Kinoshita Elementary showed that a packaged single-zone rooftop unit can be used effectively with displacement ventilation. A four-ton packaged unit was modified to include a Copeland DigitalScroll variable-capacity compressor, which can "turn down" the cooling output to as low as 10% of full capacity. The unit also featured an integrated economizer, a variable-speed drive for varying supply fan speed, and a controls package that allows for adjustment of system setpoints and settings. The system also used a variable air volume control strategy, similar to that used at Coyote Ridge. The supply air volume varies from a minimum of 450 cfm to a maximum of 1200 cfm to control the space temperature to the setpoint. The compressor output is modulated to control the SAT. The objective of the second demonstration was to demonstrate viability of DV and to show that energy savings can be realized.

Both classrooms utilize two displacement diffusers mounted along the interior wall. Since classrooms in these climates have minimal heating needs once they are occupied, heating is also supplied through the low-velocity diffusers. Heating is needed primarily for morning warm-up before occupancy. Coyote Ridge Elementary used two quarter-round diffusers installed in the corners of the classroom. Kinoshita Elementary used two half-round diffusers located along the interior wall (see Figure 1).

Figure 1. Displacement Diffusers, Kinoshita Elementary

Monitoring Objectives and Implementation

The primary monitoring objective was to compare the thermal comfort, indoor air quality and HVAC energy use of a displacement ventilation classroom to that of a control classroom. Thermal comfort is verified through air temperature measurements and surface temperature spot measurements. Measurements of carbon dioxide levels verify ventilation effectiveness, the primary IAQ benefit with DV. HVAC electricity use was also monitored over a nine-month period at both sites. Acoustic performance was evaluated as well. 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.

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. Space temperature conditions were monitored to verify that thermal stratification and other thermal comfort criteria conform to ASHRAE 55-2004 comfort standards. For each classroom, platinum RTDs (with accuracy to 0.36°F) recorded temperatures at heights of 4", 40", 66" and 90" above the floor, at three different locations. Outside air temperature, supply air temperature and return air temperature were also measured. Relative humidity was measured in the occupied zone and at the exhaust with Vaisala 50U sensors, which have accuracy to 3%. RH measurements verified that acceptable humidity levels were maintained with the DV system.

Carbon dioxide levels in the occupied zone, at the exhaust and outdoors were measured with Vaisala non-dispersive infrared transducers to an accuracy of 30ppm +/-2% of the reading. A CO_2 level in the occupied zone that is consistently lower than the concentration at the return would indicate better ventilation effectiveness than a mixing system, which has a ventilation effectiveness of 1.0.

Electricity use of the HVAC units was monitored with Magnelab 5A current transducers and WNA-3D-480P Watt-hour transducers. Both classrooms have both exterior doors 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.

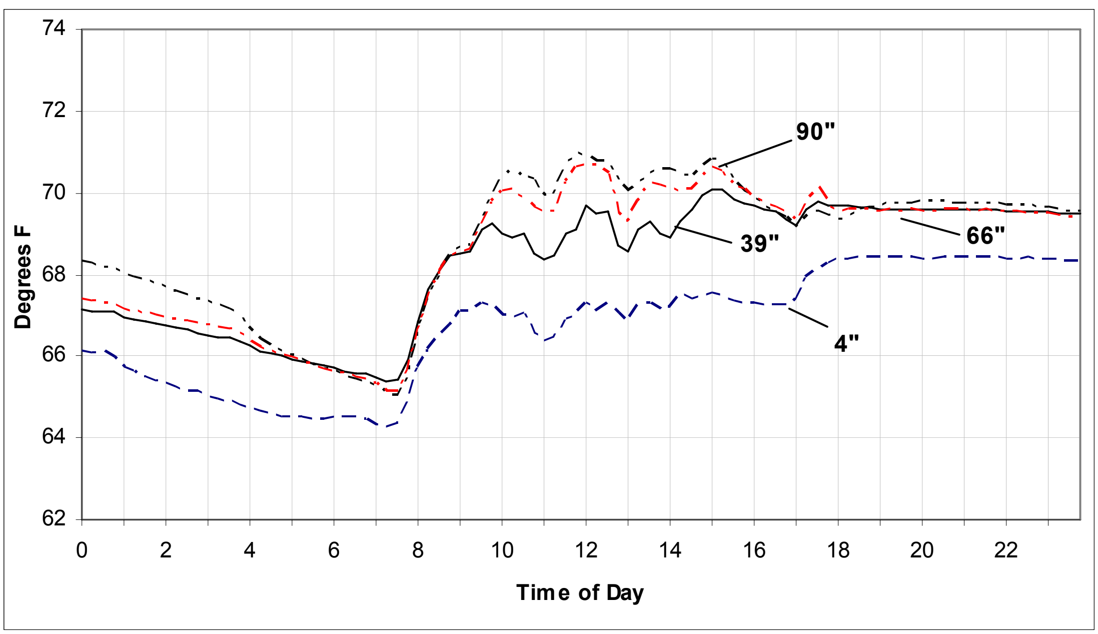
Monitoring Results

The performance of both the DV demonstration classrooms and the control classrooms at the two sites were monitored continuously over the course of the school year. The data was processed and reviewed to evaluate the thermal comfort, indoor air quality and energy performance of the DV systems. This paper presents a brief summary of the results.

Thermal Comfort and Stratification

Figure 2 shows air temperatures at four different heights in the Kinoshita DV classroom during the peak cooling season. A steady pattern of stratification is achieved in the occupied zone of the DV classrooms. The level of stratification, typically 2.0 to 2.5°F between floor level (4") and head level of the seated students (39-40"), conforms to the ASHRAE 55-2004 comfort criterion for unmixed spaces.

Figure 2. DV Classroom Temperatures, Near Exterior Wall, Kinoshita, 9/15/2005



Monitoring results of indoor space temperatures in the Coyote Ridge DV classroom (Figure 3) show that comfort and acceptable stratification levels can also be maintained in a hot, inland climate.

Figure 3. DV Classroom Temperatures Near Exterior Wall, Coyote Ridge, 9/7/2004

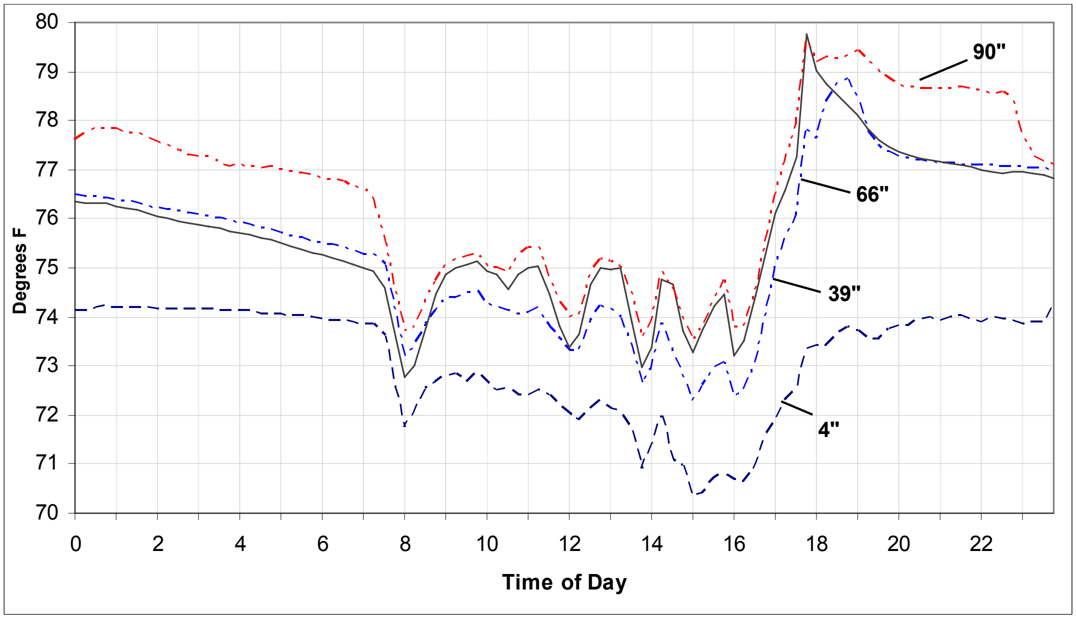
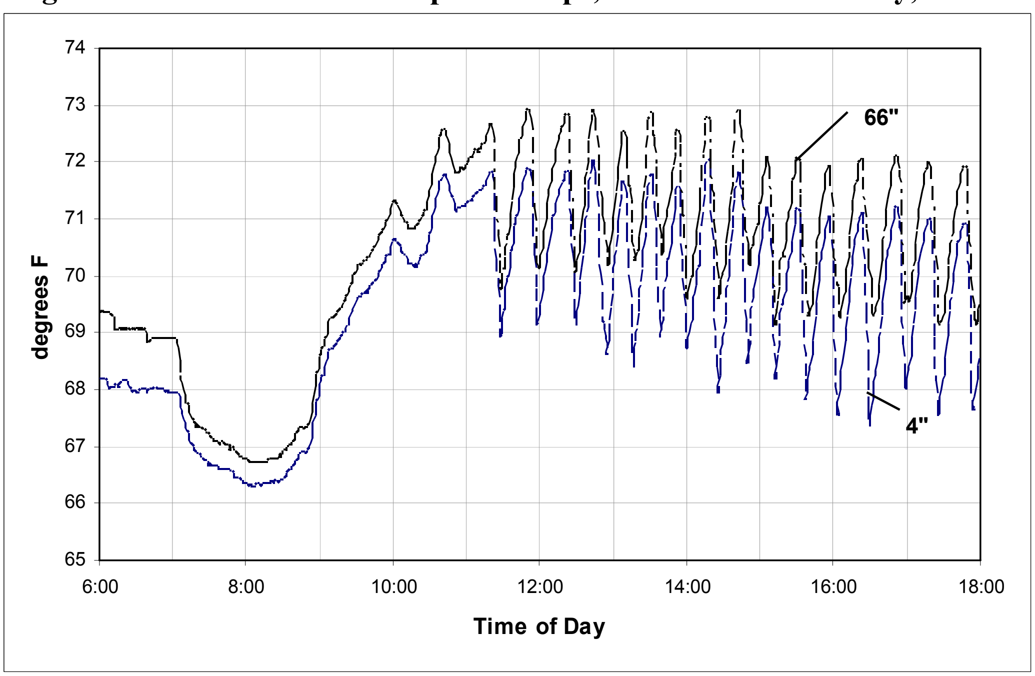


Figure 4 shows the space temperature in the mixing ventilation control classroom at Kinoshita Elementary at a height of 4"and 66" above the floor.

Figure 4. Control Classroom Space Temps, Kinoshita Elementary, 9/15/05



The fluctuation in space temperatures and supply air temperatures with a mixing ventilation system and packaged unit can compromise comfort. The steady cool supply of 65°F air that is characteristic of DV can provide improved thermal comfort. The most common HVAC system used to ventilate and condition classrooms is a packaged rooftop single-zone unit. These types of systems typically have a single compressor and relatively simple controls. They are often oversized to meet conservative estimates of occupant and equipment loads. Since the space cooling load is often much lower than at design conditions, the compressor will cycle on and off to meet the space load. Large fluctuations in room temperature can result.

It is commonly known that displacement ventilation, which relies on vertical movement of heat and contaminants towards a ceiling exhaust, is not designed for heating. Buildings in colder climates, or spaces that incur large radiant heat losses at exterior glazing, can benefit from a supplemental perimeter heating system. However, this does not preclude the use of low-velocity "displacement" diffusers for heating. In California classrooms, little heating is needed during the school day, as heat gains from students and equipment offset envelope and infiltration losses to the outdoors. For the demonstration classrooms, the diffusers operated in heating as well. At Coyote Ridge, the heating supply temperature was controlled to a maximum of 80°F to 85°F by the hydronic coil. By using the displacement diffusers in heating as well, the need for a costly supplemental heating system is avoided. The Capistrano system used a low-output gas heating and used the same low-velocity diffusers used for heating.

Thermal comfort in heating was acceptable in the DV demonstration classrooms, as indicated by both monitoring data and comfort survey results. Figure 5 shows space temperatures in the DV classroom during the peak heating season. The use of the low-velocity displacement diffusers in heating provided acceptable thermal comfort.

Indoor Air Quality

The primary indoor air quality (IAQ) benefit of the displacement ventilation system is improved ventilation effectiveness. In each classroom, carbon dioxide concentrations were monitored in the occupied zone, at the return, and at the exhaust. 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 5. Coyote Ridge DV Classroom Space Temps, January 12, 2005

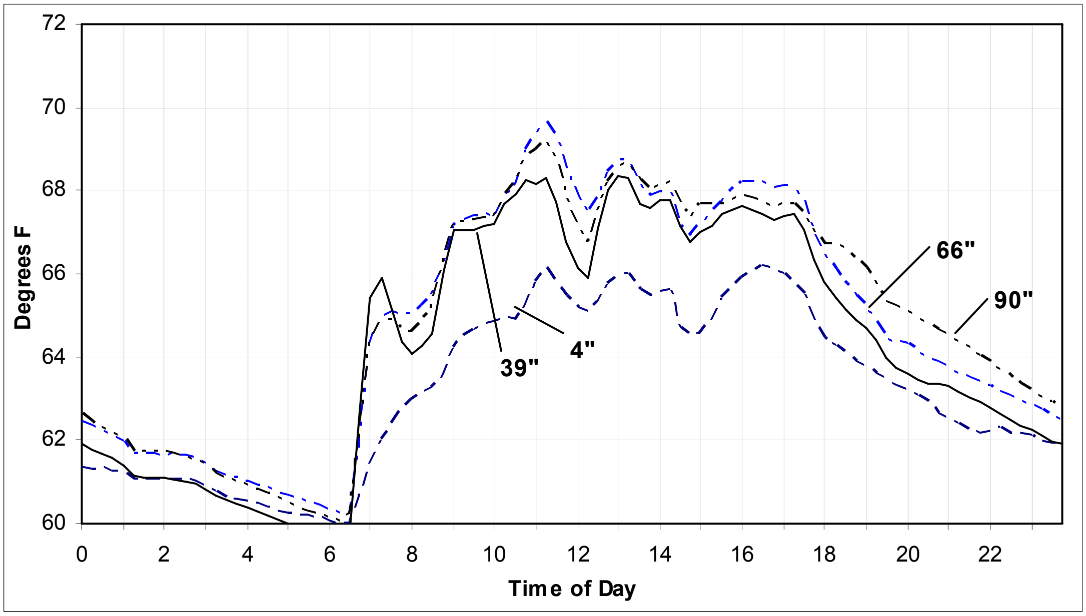
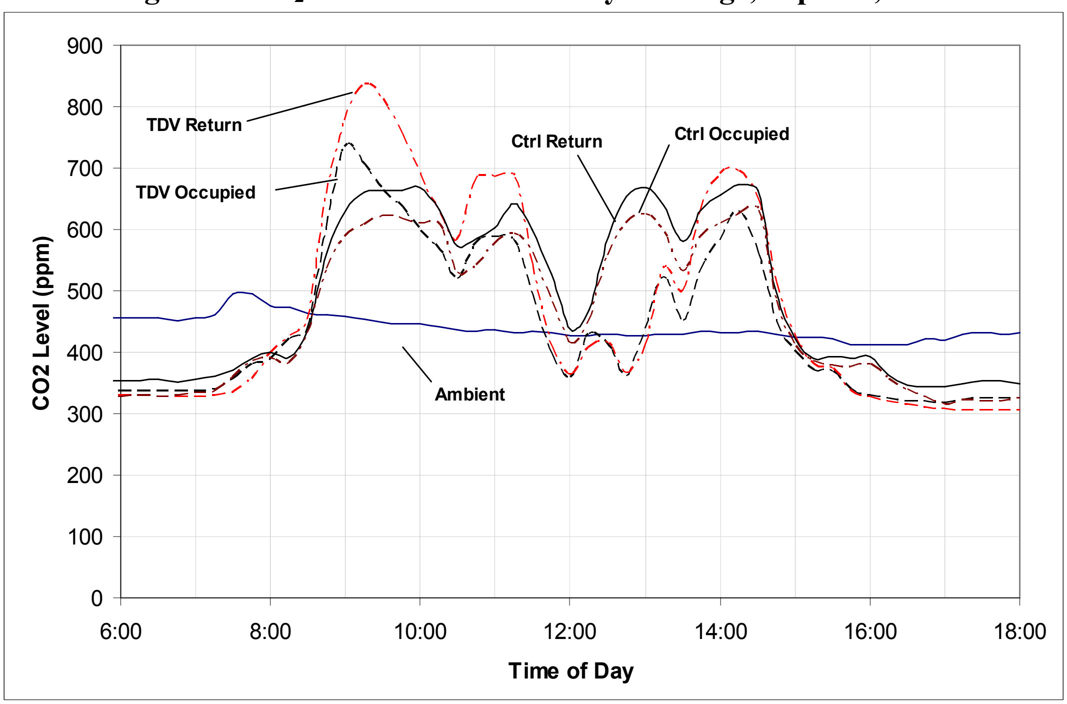


Figure 6. CO_2 Concentrations at Coyote Ridge, Sept. 27, 2004



Monitoring results from Coyote Ridge showed that, for the mixing ventilation control classroom, the CO_2 concentration was actually higher in the occupied zone than at the return. While the overall CO_2 levels were acceptable, this was an indication that the mixing system had low ventilation effectiveness.

Monitoring results of indoor air quality from Kinoshita Elementary (Figure 7) also indicate good ventilation effectiveness, with low CO_2 levels in the occupied zone.

Figure 7. CO_2 Concentrations at Kinoshita Elementary, Sept. 15 2005

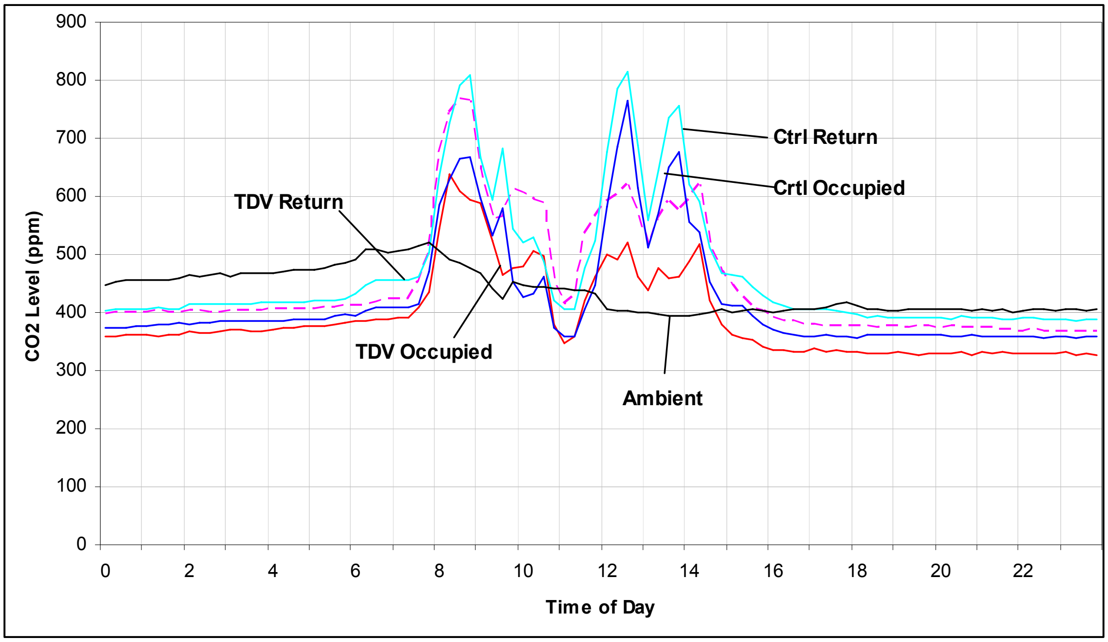
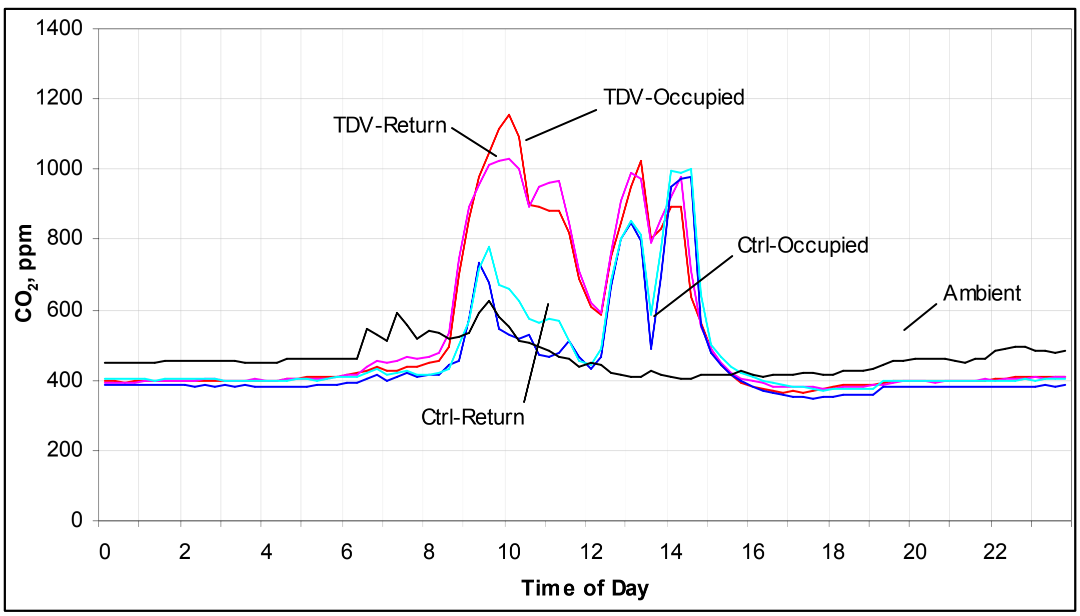


Figure 8. CO_2 Concentrations at Coyote Ridge Elementary, Jan. 27, 2005



With the introduction of a minimum of 15 cfm of outside air per occupant, CO_2 levels are well below the limits recommended by ASHRAE 62.1-2004.

During the heating season, the low-velocity air distribution system using the displacement diffusers can have reduced ventilation effectiveness. Since heating mostly occurs during unoccupied periods, this was not an issue for the demonstration classrooms. ASHRAE 62.1-2004 defines ventilation effectiveness in heating for low-velocity air supply and ceiling return at 0.7, compared to 0.8 for a mixed overhead heating air supply (with a SAT at least 15°F above the room temperature). Figure 8 shows monitored carbon dioxide levels during a representative heating day at Coyote Ridge, January 27, 2005. The DV classroom does have a higher CO_2 concentration than the control classroom in the morning, but it is generally within the ASHRAE 62.1-2004 recommended limit. Moreover, the ventilation effectiveness is acceptable for the DV system in heating.

The CO_2 concentration levels in the occupied zone of the control classroom are much lower in the morning hours. This can be at least partially attributed to the effect of natural ventilation: the exterior door, which was continuously monitored with a magnetic contact switch, was left open during much of the morning. The heating performance of the DV system is acceptable in the demonstration classrooms. However, diffuser designs that provide a means to increase discharge air velocity in heating by automatically reducing the opening area may provide improvement during the heating season.

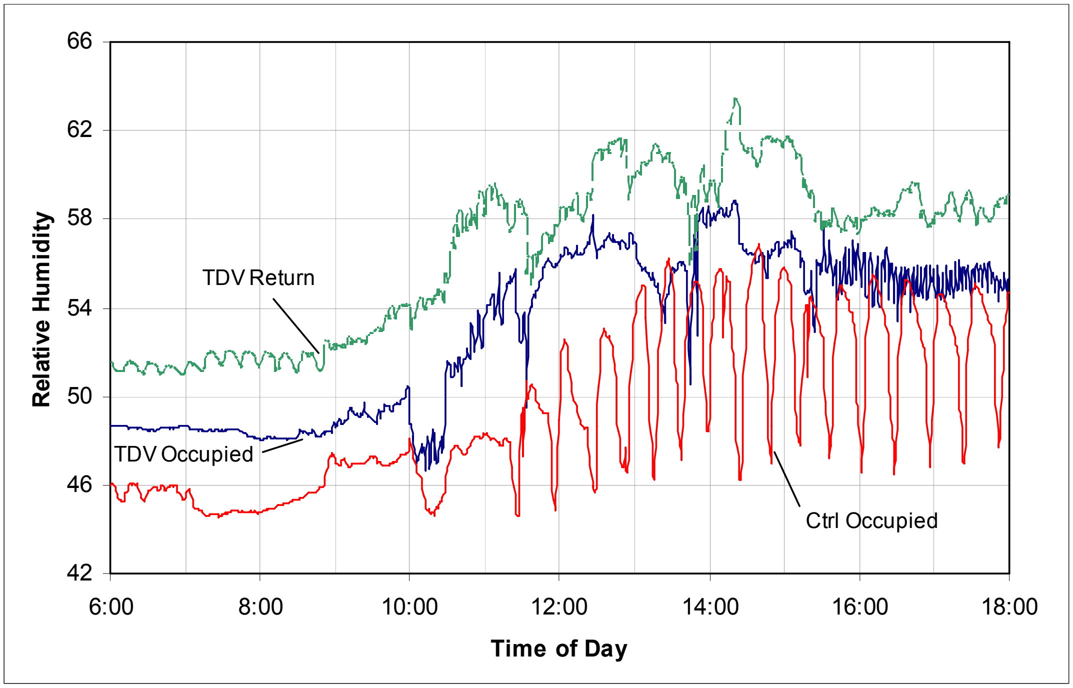
Relative Humidity

Some engineers have pointed out that with the use of a higher supply air temperature, displacement ventilation may not provide sufficient dehumidification in some cases. The results from Kinoshita show that the humidity is maintained to acceptable levels in the DV classroom (Figure 9). 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. The design can provide improved humidity control through the elimination of cycling.

In most California applications, the use of sensible cooling alone is adequate to maintain indoor humidity levels. However, in many other parts of the country, dehumidification will be required to remove moisture from the outdoor air. For cases where high humidity is a concern, options such as return air bypass can be used for addressing humidity without requiring reheat (Architectural Energy Corporation, 2005).

Figure 9. Relative Humidity, Kinoshita Elementary, Sept. 15, 2005



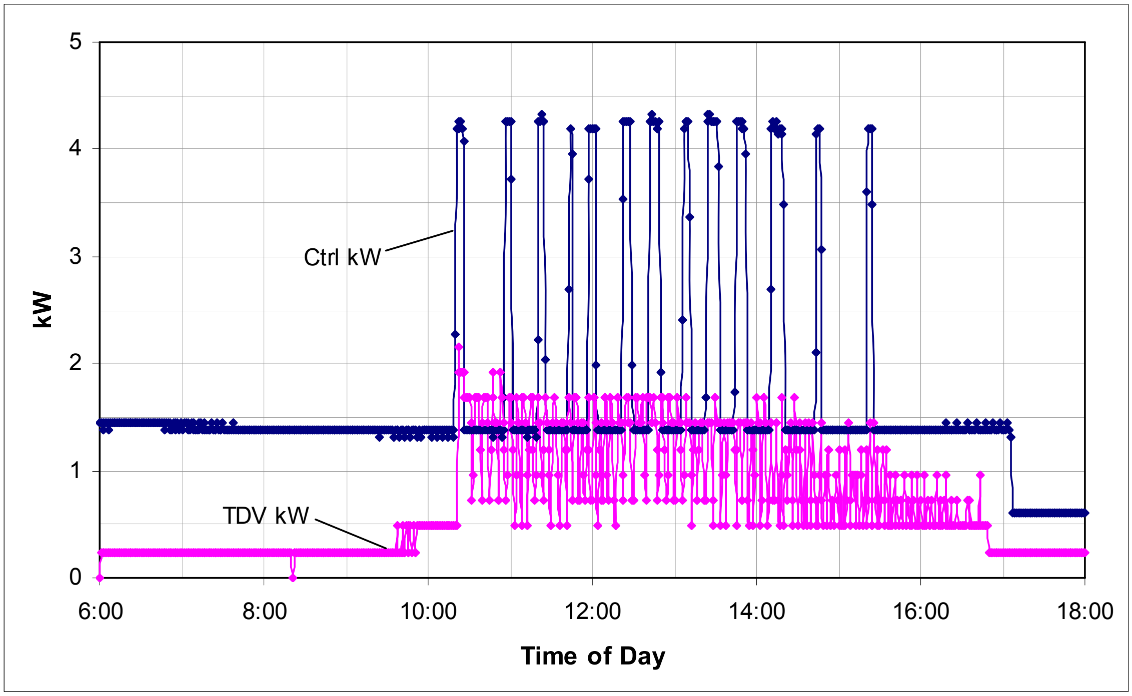
Acoustics

DV helps meet demanding acoustic requirements for classrooms. The ANSI S12.60 Acoustics Standard and the Collaborative for High Performance Schools both recommend a background noise level of 35 dBA for core learning spaces. This is difficult to achieve when packaged rooftop units are located above classrooms. DV provided a remarkable improvement in classroom acoustics at Kinoshita Elementary. 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, which impacts both comfort and air quality.

Kinoshita: Demonstration of Energy Savings

Kinoshita Elementary demonstrated the energy savings that can be achieved with DV. Electricity and gas use of the HVAC units was measured at 1-minute intervals. Figure 10 shows measured electricity use of the two HVAC units on Nov. 2, 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 both reduces peak demand and reduces compressor cycling, resulting in improved comfort. Compressor cooling output varied between 10% and 30% of full capacity, with a corresponding reduction in power.

Figure 10. HVAC Electricity Use, Kinoshita Elementary, Nov. 2, 2005



An energy savings of 39%, compared to the control unit, was realized with the Kinoshita DV system in the fall of 2005 (Table 1). Initially, the higher energy use of the DV system in August and September was partially caused by the fact that the DV classroom was conditioned to a cooler space temperature in the occupied zone, as evident from temperature monitoring. After the thermostat settings were modified to align the temperatures of the DV classroom with those in the mixing classroom, and after making some configuration changes to verify proper economizer operation, a significant energy savings was achieved later in the fall. The demonstration classroom and associated control classroom will continue to be monitored through the spring 2006 season, to determine if the energy savings achieved in late fall will occur throughout the cooling season.

Table 1. Kinoshita HVAC Energy Comparison

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

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% is sufficient to condition the space. Since fan power varies with the cube of fan speed, this provides a large reduction in fan energy.

Teacher feedback has been positive in the displacement ventilation classroom. The teachers in the two classrooms were given bi-weekly surveys to obtain their perceptions of acoustics, indoor air quality and thermal comfort. On average over the monitoring period, the teachers in both displacement classrooms also gave the DV systems higher marks for both acoustics and thermal comfort.

Conclusions

Displacement ventilation provides effective ventilation and excellent thermal comfort for California classrooms. Acoustic benefits alone are a compelling reason to use DV. The demonstration classrooms confirmed that displacement ventilation provides good thermal comfort for California classrooms. Accommodation of the DV system does not require changes in classroom building design. Each demonstration classroom included a ceiling height of 9 feet, with a higher ceiling at the skylight well, and a building envelope that is typical of new construction. The DV systems did not create problems with cold drafts at the floor. The systems provided consistent thermal stratification in the space and good ventilation effectiveness. The effects of occupant activity, and opening of doors and windows, limit the amount of stratification that is achieved in practice. However, the Kinoshita demonstration showed that energy savings are significant, due to the increased opportunity for use of economizer cooling. The systems maintain acceptable indoor humidity levels and provide adequate comfort and IAQ during the winter as well.

Acknowledgements

This research was funded by the California Energy Commission PIER (Public Interest Energy Research) Program. The authors would like to recognize funding contributions from San Diego Gas & Electric for the Kinoshita demonstration, and contributions from manufacturing partners the Halton Company, Carrier and Trane. Additional information on the project, as well as more detailed results of the monitoring, can be found on the program website, http://www.archenergy.com/ieq-k12, or by contacting authors of this report.

References

ANSI/ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigeration and Air Conditioning Engineers, 2004.

ASHRAE Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality.* American Society of Heating, Refrigeration and Air Conditioning Engineers, 2004.

Architectural Energy Corporation, 2005. *Design Brief: Displacement Ventilation.* Energy Design Resources, 2005.