Thermal Displacement Ventilation (TDV) in Schools: Improving Indoor Air Quality and Saving Energy

Andrey Livchak, Halton Company
Charles Eley, Architectural Energy Corporation
Zeqiang Sun, Halton Company
John Arent, Architectural Energy Corporation
Vern Smith, Architectural Energy Corporation

ABSTRACT

Thermal displacement ventilation (TDV) is a promising technology for schools and other buildings. The potential energy efficiency, health, and acoustic benefits offer promise as California and other states prepare to spend billions on new schools and major modernization. This paper presents some results from a PIER-funded study of the technology evaluated with computational fluid dynamics and full-scale model testing.

In 1995, the Government Accounting Office concluded that 25% of the nation's schools are plagued by indoor air quality (IAQ) problems. A few years later the Environmental Protection Agency (Johnston & Davis 2001) reported an even higher percentage of schools having IAQ problems. Most of these IAQ problems can be attributed to poor ventilation. TDV, which has been used since the late 1980s in Northern Europe and only more recently in U.S. schools (Turner 1999; Holland & Livchak 2002), disproves the common perception that improving IAQ in an air-conditioned space must result in higher energy consumption.

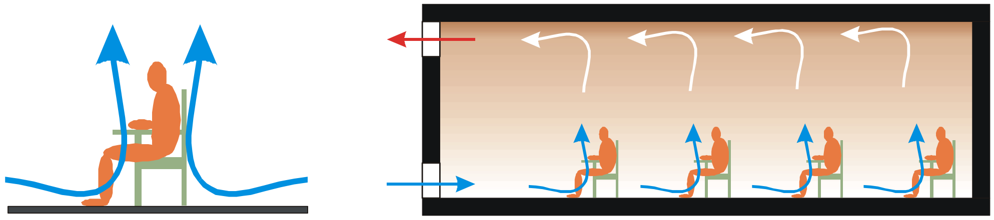
What Is It?

Most classroom air conditioning systems use overhead mixing ventilation to deliver cool air (about 55ºF) at the ceiling level. Air is supplied at a high velocity to provide efficient mixing of supply air with room air, to provide uniform temperature throughout the space, and to dilute contaminants with fresh supply air. This system of ventilation has several drawbacks: it can circulate germs, promoting exposure to illness, and it can be noisy and/or drafty – the high-speed air can whistle as it leaves the diffuser, creating possible drafts and making it harder for the students to hear the teacher.

Another problem with overhead mixing ventilation is that it does not provide uniform ventilation. That is especially true with variable volume systems, when ceiling diffusers are delivering less than the design airflow. Using a ceiling diffuser to lower the supply air velocity results in cold air coming into the room in only a few places, leaving the rest of the room at higher temperatures. And, without fresh air, carbon dioxide levels can build up and other pollutants can accumulate. Air quality deteriorates, the air becomes stuffy, and the students can become drowsy.

By contrast, all TDV systems deliver fresh air at the floor instead of the ceiling level. The air is heated or cooled so that it enters the room at about 65ºF, considerably warmer than with a conventional air conditioning system. The diffusers are larger so that the air flows into the space at a low speed. Since the 65ºF air is cooler than the rest of the air in the room, it spreads by gravity all along the floor, forming a continuous layer of cool air that displaces contaminants and heat into the upper part of the space.

Figure 1. Airflow Using Thermal Displacement Ventilation



Source: Halton Company 2004

Every student in the room, as well as the teacher, produces heat. As body heat warms the cooler air at the floor, it then rises straight up over the bodies. The effect of air rising up over a warm object is called a thermal plume.

Since the air moves straight up, and all supply air is delivered at the floor level, each person basically has his or her own supply of outside air ventilation. If a student coughs or sneezes, there is less chance that the germs will be passed on to others. Used air and pollutants collect at the top of the space where they are exhausted.

A classroom with TDV looks a lot like any other classroom. A higher ceiling benefits displacement ventilation because the warmer, used air can better accumulate at the top of the space. High ceilings create a better acoustic environment, and also allow space for indirect/direct lighting systems, which do a better job of illuminating the walls and ceiling. Diffusers can be recessed into the wall, mounted in a corner, or positioned under casework. Since the cool air leaves the diffuser at a low speed, there are no drafts. The system is quiet and, as discussed above, provides for excellent IAQ.

The Prototype Classroom

This study uses a typical California classroom. Further work will evaluate TDV in a variety of other configurations. The base case classroom is defined to comply with the minimum requirements of the California energy efficiency standards – but to exceed these standards when common practice does. The prototype was developed through both an evaluation of code minimums and a review of current school plans, which had been recently submitted to the Bay Area regional office of the State Architect. Average data from the Nonresidential New Construction (NRNC) Database were used to determine representative window areas, occupancy, and equipment schedules.

High ceilings are desirable for TDV systems, so the baseline prototype has a ceiling height of 10 ft. The baseline prototype is wood frame construction with insulation levels meeting the 2005 Title 24 Energy Efficiency Standards (CEC 2003). Window area was set to match NRNC average data for school construction, and internal heat gains are set to be consistent with new construction. A class size of 20 students, the target for K-3 schools under California's voluntary Class Size Reduction Program, is assumed. The occupant, lighting, and equipment schedules were set to 100% of the full capacity during school operating hours to determine design cooling conditions.

Table 1. Baseline Prototype Specification

Parameter	Value	Source
Classroom Size	32 ft x 30 ft x 10 ft high	DSA School Plan Review
Classroom Orientation	South facing exterior wall	DSA School Plan Review
Envelope	U_{wall}=0.102, U_{roof}=0.049	Title 24
Fenestration	82ft^2 of window area; U=0.55	NRNC Database and Title24
Lighting	1.0 W/ft^2	CHPS Design Guide
Occupants	20 occupants, 200Btu/h sensible heat gain per student, 120Btu/h latent gain	Classroom Size Reduction target for student count; ASHRAE 2001 Fundamentals for heat gain
Equipment	4 computers at 125W each	DSA Plan
Occupant, Equipment, Lighting Schedules	Set to 100% from 8AM to 3PM	School hours from NRNC Database

Source: Halton Company

Full-Scale Validation of the Computational Fluid Dynamics (CFD) Model

Traditional design methods are not effective for classrooms with TDV, because they are based on the assumption that the space has a uniform temperature from floor to ceiling and that the air is well mixed. TDV works because there is a significant temperature difference between the floor and the ceiling, which drives air movement through buoyancy.

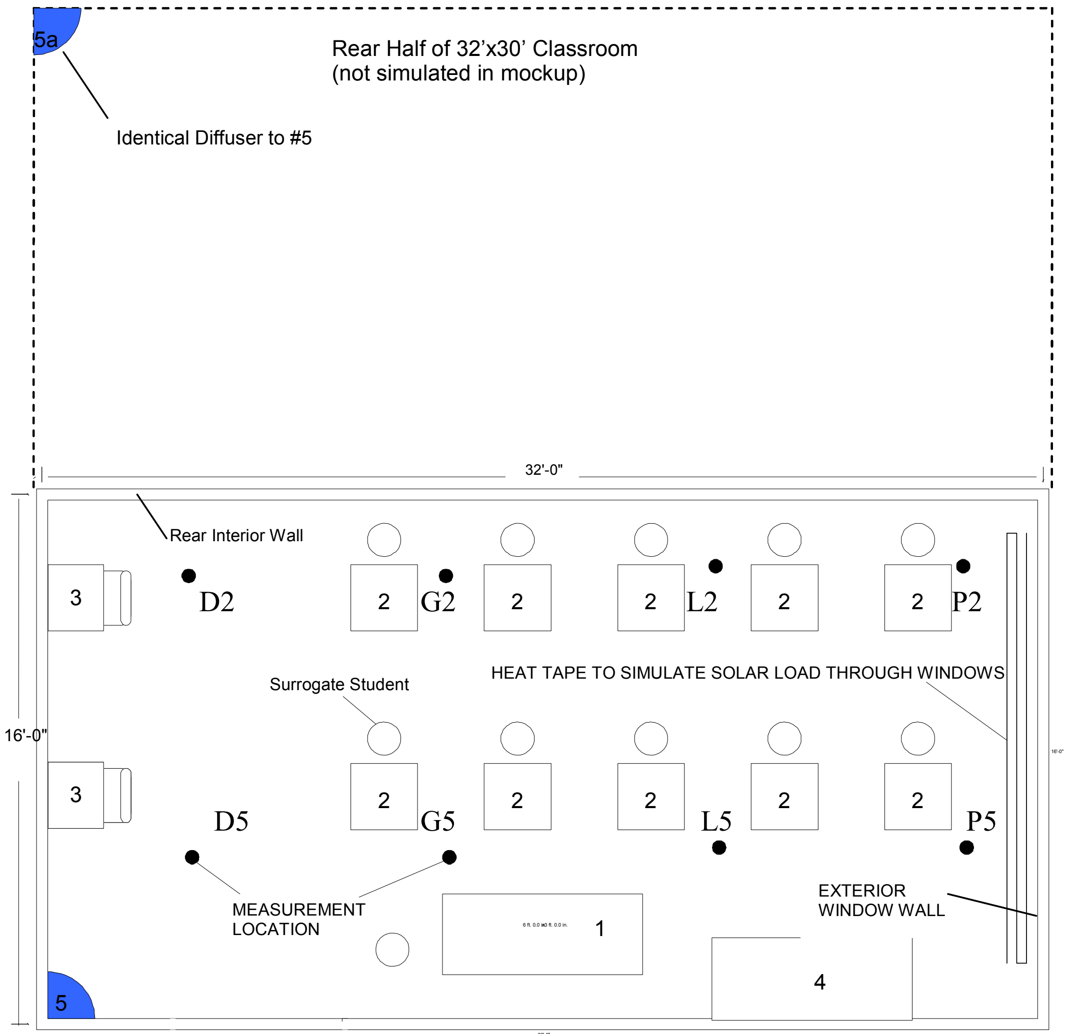
CFD analysis is needed to model and study the complex dynamics associated with TDV. CFD is an established, state-of-the-art scientific approach for quantitative prediction and analysis of fluid flow, heat, and mass transfer in a variety of situations. This study used a commercially available CFD software tool (Airpak 2.1.10 2002) by Fluent. The Airpak/Fluent package employs a finite-volume formulation of the governing differential equations used in CFD. The package can model basic fluid flow, heat transfer, turbulence, radiation heat transfer, and contaminant transport.

The zero equation turbulence model by Chen and Xu (1998) was chosen for the project; it is developed especially for the indoor air flow simulation. This turbulence model works well to predict a stable flow, which is a characteristic of displacement ventilation. The discrete ordinate radiation model was chosen to account for the radiation heat transfer.

To validate and calibrate the CFD model, a full-scale mockup of half of the prototype classroom was constructed and tested at the Halton research and development facilities. The mockup facility has interior dimensions of 16 ft x 32 ft x 10 ft. A plan view of the mockup is shown on Figure 2. The main objectives of the mockup tests were to:

1. Validate the Airpak CFD software package that will be used to analyze TDV applications for different classroom configurations.
2. Determine TDV design parameters for the reference classroom under the design cooling load conditions.

Figure 2. Mockup Plan View



Dashed lines indicate the back half of the prototype 32'x30' classroom. Source: Halton Company 2004

The thermal loads in the mockup are equivalent to those in the prototype classroom, but scaled to represent half of the floor area. The longest interior wall of the mockup is identical to the one in the representative classroom. The heat gains through the walls and roofs were determined from the DOE-2 simulation of the classroom prototype and used for the mockup. Therefore, the magnitude and distribution of the envelope, lighting, and equipment heat gains in the 32 ft x16 ft mockup classroom are identical to the representative classroom. Also, since the back wall of the 32 ft x 16 ft classroom is an interior wall with approximately the same temperature as the room, the heat transfer from the wall to the space is negligible.

The mockup was furnished with 10 student desks, 10 metal cylinders (40 in. high and 12 in. in diameter) with a 60-Watt light bulb inside to simulate the heat from a student. Two computers and fluorescent lights were installed at the ceiling with a lighting power density of 0.9 W/ft². The rest of the loads, such as solar and heat transfer though the envelope, were simulated with heat tape.

Existing applications of displacement ventilation systems in schools (Turner 1999; Holland & Livchak 2002) use two displacement diffusers installed at the corners at the interior wall (opposite to exterior wall). This approach minimizes the number of diffusers required to ventilate the space and uses the flow from displacement diffusers in the most efficient way, as the cool supply air moves towards the strongest heat source – the exterior wall. The mockup validated this approach for a typical classroom with the cooling loads corresponding to California climate zone 12 (Sacramento). Temperatures and velocities were measured across the occupied zone and compared to the thermal comfort requirements per ASHRAE Standard 55.

Figure 3. Photograph of Classroom Mockup

Source: Halton Company 2004

Table 2. Cooling Load Specification

	Load Representation		Total assigned values, Btu/h (W)	
Actual	Mockup	CFD	Mockup	CFD
Students	Dummies	Cylinder blocks	2047 (600)	2047 (600)
Teacher	Adult	Cylinder block	341 (100)	341 (100)
Computers	Computers	Prism blocks	853 (250)	853 (250)
Lighting; heat transferred through ceiling	Lighting, heat tape	Heat source below ceiling	input: 4026 (1180), loss: 863 (253)**, net: 3163 (927)*	3163 (927)*
Heat transferred through exterior wall, window and floor; solar radiation	Heat tape on window and floor	Wall with heat flux	3412 (1000)	3412 (1000)
Total of all loads			9816 (2877)	9816 (2877)

* CFD simulation accounts for the net heat gain to the space as measured in the mockup.
** Heat loss through the ceiling = total heat gain in the mockup - total energy exhausted

Source: Halton Company 2004

One diffuser in the mockup is equivalent to two diffusers in the full-size classroom. Temperature and velocity were measured in the mockup at eight locations shown in Figure 2. At each location data were taken at 4 in., 10 in., 20 in., 30 in., 47 in., 67 in., 90 in., and 110 in. from the floor. Supply and exhaust airflows and temperatures were measured as well.

Test conditions for the mockup and CFD simulations are listed below:

- Supply air flow rate: 623 cfm (294 l/s) @ 64.6°F (18.1°C)
- Displacement diffuser: Halton AFQ 315.

Thermal conditions in the mockup were allowed to stabilize for at least 12 hours prior to taking temperature and velocity measurements. Room air temperatures measured in the mockup are compared to the results from the CFD simulation and shown in Figure 4. While there is excellent agreement, the CFD model somewhat overestimates air temperature near the ceiling, which is explained by the fact that CFD model does not account for some heat losses through the ceiling and accounts for 100% of the load from lights within the space. However, this minor discrepancy does not affect the ability of the CFD model to predict air temperature within the occupied zone (6 ft or 1.8 m from the floor level).

Both measured and predicted air velocities within the occupied zone do not exceed 50 fpm.

Results of the CFD Analysis

After the CFD model had been validated, the prototype classroom (described above) was modeled using the Airpak/Fluent CFD package. Supply airflow was set to 1100 cfm and delivered at 65°F. This was determined through an iterative process to achieve a maximum temperature difference of 5ºF between 4 in. and 67 in. from the floor and to maintain an average temperature in the occupied zone of 74-75ºF using two Halton AFQ 315 displacement diffusers installed in the corners at the interior wall (Figure 5). Cooling loads for the modeled classroom are listed in the Table 3. For comparison, a traditional mixing ventilation system for the same room is also simulated. This mixing system supplies 847 cfm of air at 57°F through four ceiling diffusers to achieve same air temperature within the occupied zone.

Figures 6 and 7 show the temperature distribution within the classroom and Figure 8 shows the CO_2 concentration in classroom close to the exterior wall – the most distant location from the displacement diffusers. The distribution of carbon dioxide exhaled by the students and teacher was simulated to analyze the indoor air quality with TDV. Based on ANSI/ASHRAE Standard 62-2001, Appendix C, each student and the teacher are assumed to exhale 0.31 l/min of CO_2. Concentration of CO_2 in supply air is assumed to be 350 ppm, which is a typical value for outside air. 100% outside air configurations are assumed to be used for both displacement and mixing cases for easy comparison. The results show a much lower concentration of carbon dioxide in the breathing zone for TDV (Figure 8).

Figure 4. Comparison of Predicted and Measured Temperature Profiles

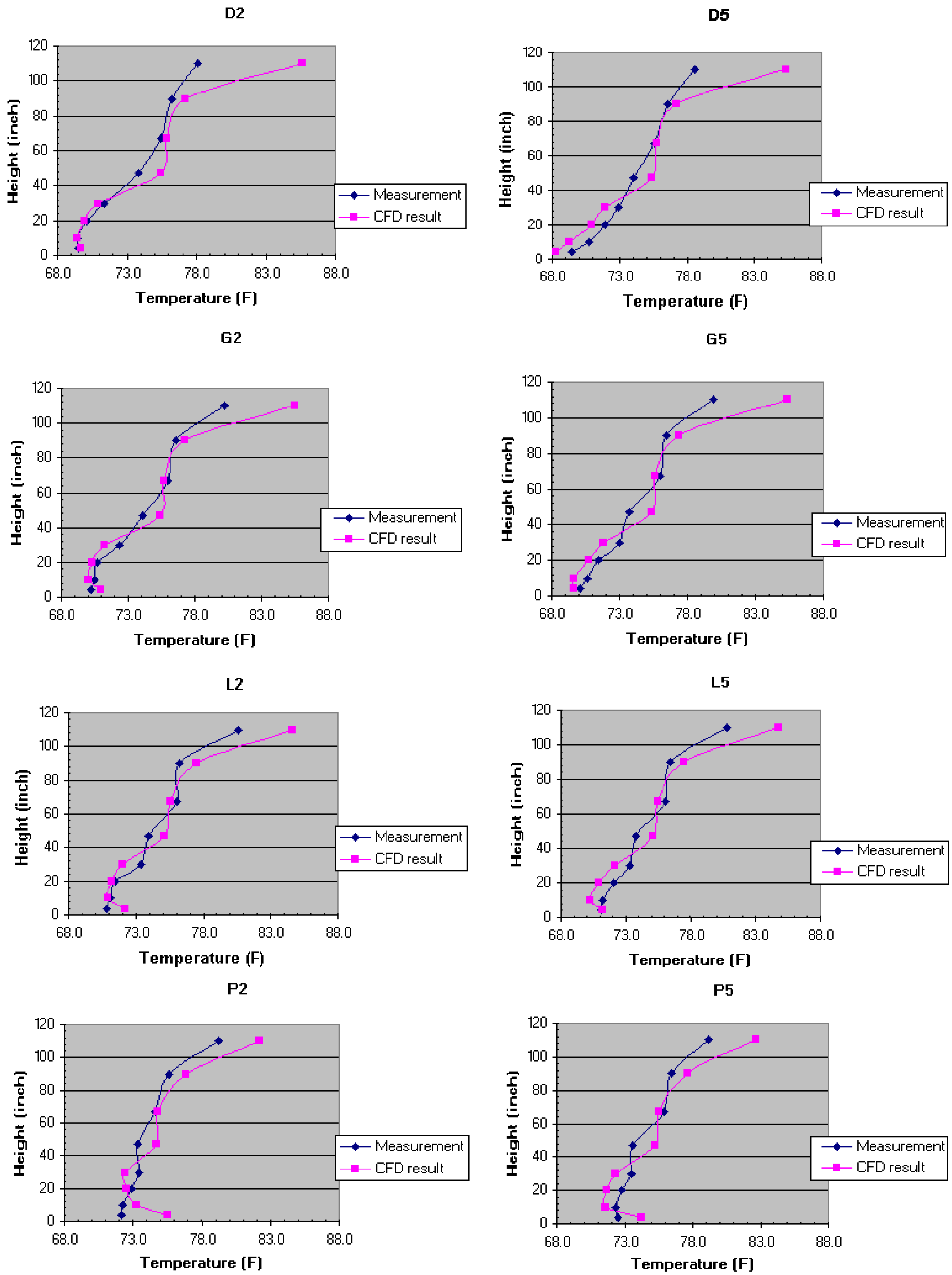
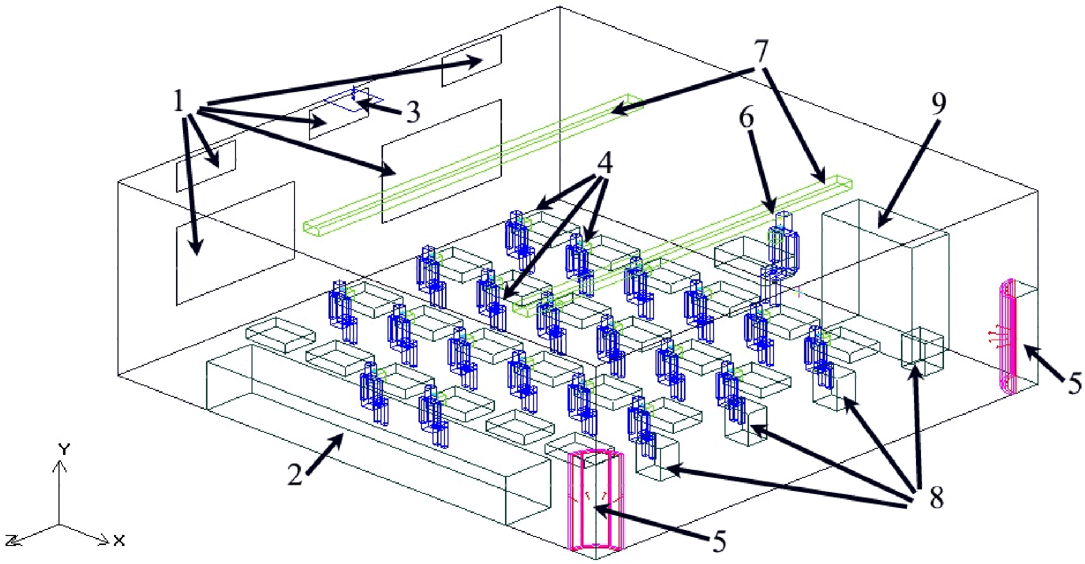


Figure 5. CFD Classroom Model



Key: 1 windows; 2 wall cabinet; 3 return; 4 students and desks; 5 AFQ315 displacement diffuser; 6 teacher, 7 lights; 8 computers; 9 audio/video cabinet; Source: Halton Company 2004

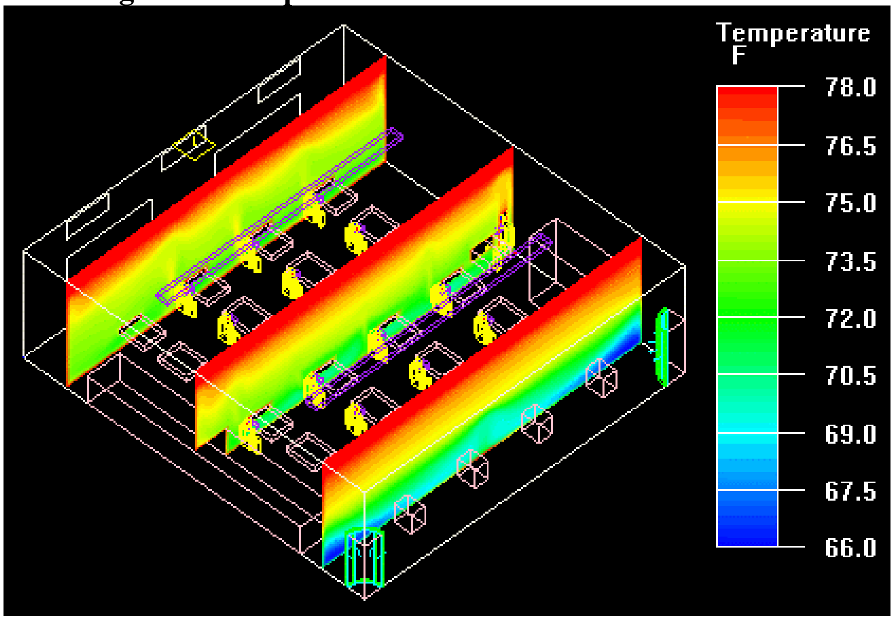
Table 3. Summary of Cooling Loads for Prototype Classroom

Load	Sensible, Btu/h	Latent, Btu/h
External wall	513	
Roof	1377	
Window, conduction	1097	
Window, solar radiation	4660	
Occupants	3732	2625
Lighting	2575	
Equipment	1440	
Total Sensible*	**15394**	**2625**

Source: Halton Company 2004

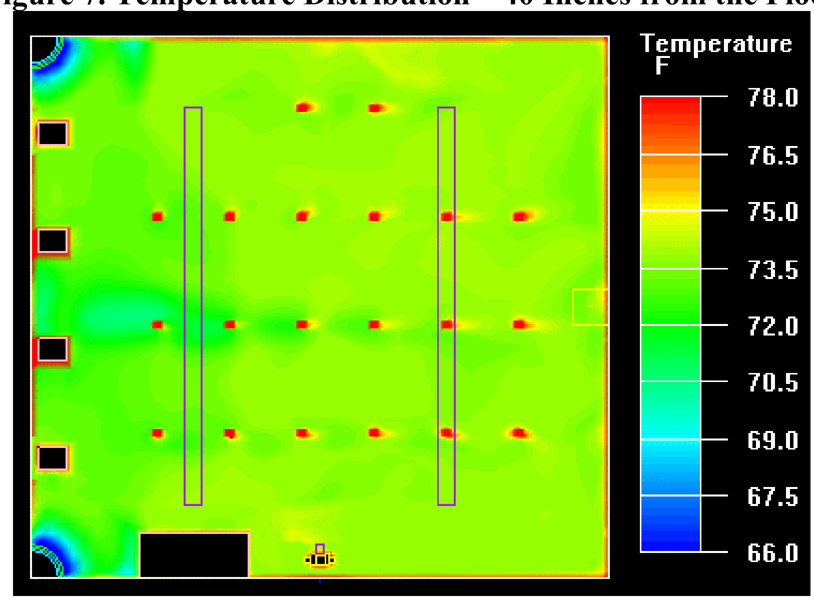
CFD simulation results demonstrate that the modeled supply airflow of 1100 cfm at 65°F is sufficient to maintain temperature in the classroom's occupied zone between 72ºF and 75°F. Figure 8 shows that carbon dioxide stratifies in the classroom, with TDV having a higher concentration in the upper part of the space and a lower CO_2 concentration at the breathing level. Figure 9 demonstrates higher effectiveness of TDV as a system with lower mean age of air in the occupied zone.

Figure 6. Temperature Distribution – Vertical Slices



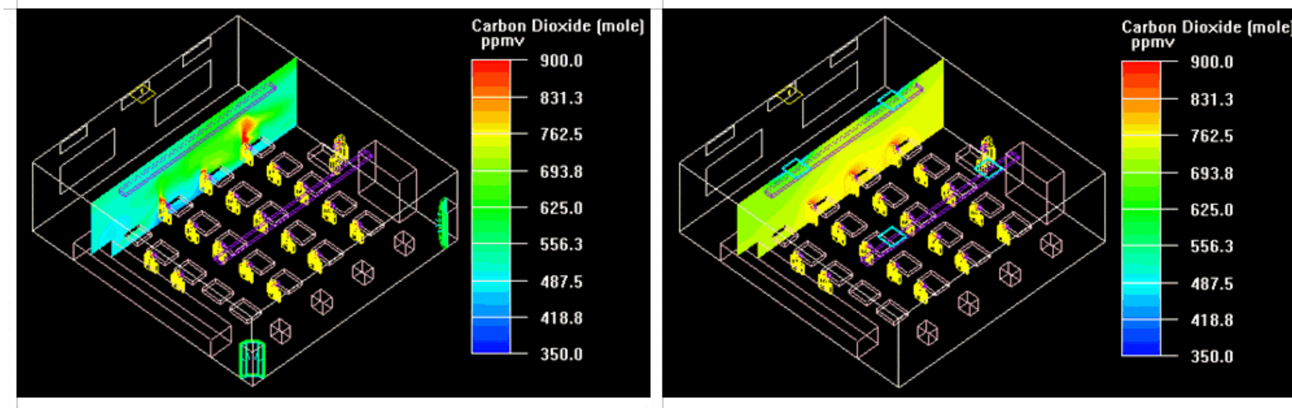
Source: Halton Company 2004

Figure 7. Temperature Distribution – 40 Inches from the Floor



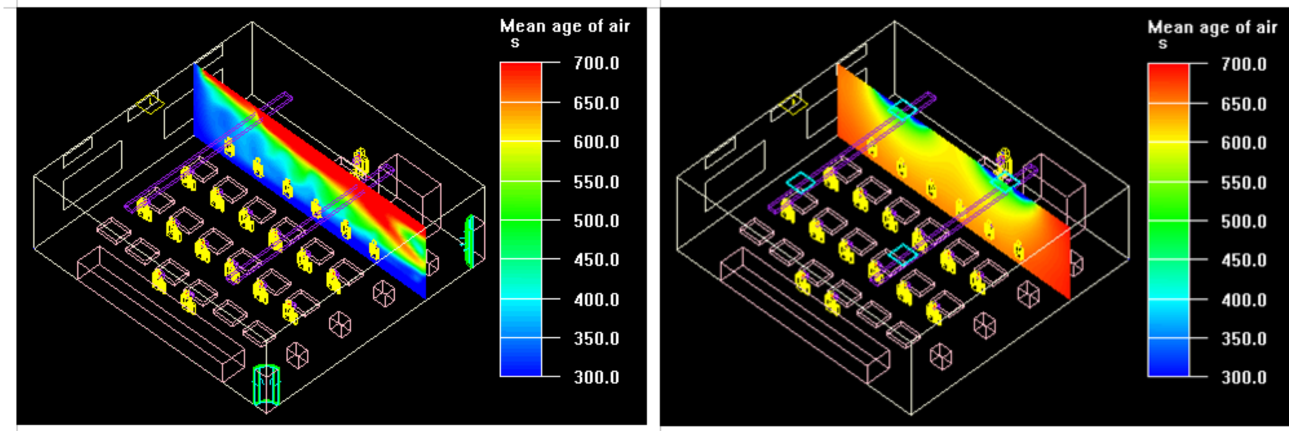
Source: Halton Company 2004

Figure 8. CO_2 Concentration Comparison – Displacement (left), Mixing (right).



Source: Halton Company 2004

Figure 9. Mean Age of Air Comparison – Displacement (left), Mixing (right)



Source: Halton Company 2004

Comparing Annual Energy Consumption – TDV Versus Mixing Ventilation

Table 4 presents data comparing annual energy consumption by the chiller for TDV and conventional mixing ventilation system required to air-condition the prototype classroom.

- Total sensible load is 15.4 kBtu/h.
- Design space air temperature is 74°F.
- Operating hours are 5 days/week and 8 hours/day (7AM - 3PM).
- Cooling design conditions are 1% from *ASHRAE Handbook 2001*.
- TMY2 hourly weather data are used to analyze annual energy consumption.
- Chiller coefficient of performance COP is assumed to be 3.0 for all systems.
- Supply air temperature is 65°F for TDV and 57°F for mixing system (assuming 2°F fan and duct heat gain).

Table 4. Annual Energy Consumption by the Chiller TDV vs. Mixing Ventilation

	Sacramento			San Francisco			Los Angeles		
	TDV		Mixing with return	TDV		Mixing with return	TDV		Mixing with return
	All OA	Return		All OA	Return		All OA	Return	
Supply air temperature, °°F	65	65	57	65	65	57	65	65	57
Supply airflow, cfm	1100	1100	847	1099	1099	847	1103	1103	850
Return air temperature, °°F	78.1	78.1	74	78.1	78.1	74	78.1	78.1	74
Outside Airflow, cfm	1100	315	315	1099	315	315	1103	315	315
Cooling Capacity, ton	3.3	2	2.1	1.5	1.5	1.5	1.8	1.6	1.6
Cooling hours	598	598	1088	220	220	827	643	643	1628
Annual cooling energy, MWh	1	0.8	1.3	0.2	0.2	0.6	0.7	0.5	1.4

Data in Table 4 indicates that TDV allows saving 38%, 67%, and 64% on annual energy consumption for cooling for Sacramento, San Francisco, and Los Angeles, respectively. The cooling energy savings for the coastal climates of San Francisco and Los Angeles can be attributed to the greater amount of hours where free cooling can be used with TDV, due to the higher supply air temperature. Two configurations of TDV systems, one with 100% outside air and one with return air, are compared to the mixing ventilation case. All outside air systems are more energy efficient in San Francisco climate conditions, while TDV with return air is preferable in schools in Sacramento and Los Angeles.

Conclusions

TDV has the potential to improve thermal comfort, IAQ, and acoustics, and these features are strongly linked to student and teacher performance (Schneider 2002, 2003). While the best teachers and motivated students can achieve results under the worst possible conditions and the worst teachers may not be effective even in the absolutely best facilities, for most of us, acoustics, comfort, and air quality make a big difference. CFD simulation results demonstrate stratification of the carbon dioxide with TDV systems and reduction of CO_2 concentration at students' breathing level.

While the main benefit of TDV is a better learning environment, the system is also more energy efficient and this can save money for the school district. Less money for energy means more money for art programs, sports, computers, books, and teachers' salaries. The annual energy consumption by the chiller can be reduced from 36% to 80%, compared to a conventional mixing ventilation system. Thermal displacement systems save energy for a number of reasons:

- A substantial benefit is that economizers (or "free cooling") can be used for more hours during the year, since air is delivered at 65ºF instead of 55ºF. For most California climates, there are more than 2,000 hours in a year when the air temperature is between 55ºF and 65ºF.
- There are also energy savings during times when the air conditioning compressors must run, again because air is delivered at 65ºF and not 55ºF. This is because compression cooling or mechanical refrigeration can operate more efficiently when supply air temperatures are higher.

CFD predictions of temperatures and velocities in the classroom with TDV as well as exhaust air temperature agree well with measured data. Two cases (one case is presented in this paper) were validated and both demonstrated good agreement between the CFD simulations and the measurements. The tests show that the CFD software package (Airpak 2.1.10 from Fluent Inc.) can be used as a reliable tool to simulate TDV systems used for classroom applications.

Acknowledgements

This research was funded by the California Energy Commission PIER (Public Interest Energy Research) Program. The results in this paper only address a single prototype classroom. Additional studies are being performed for classrooms with higher internal loads, greater envelope loads and other conditions sometimes encountered in California classrooms.

References

AIRPAK 2.1 User's Guide. 2002. Fluent Inc. Lebanon, NH.

ANSI/ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy*.

California Energy Commission. 2003. *2005 Energy Efficiency Standards for Residential and Nonresidential Buildings*. Publication Number: P400-03-001 ETF. November 5.

General Accounting Office. 1995. School facilities: America's schools not designed or equipped for 21stcentury. GAO report number HEHS-95-95. Washington, D.C.: General Accounting Office. ED383056.

Holland D. and Livchak A. 2002. "Improving indoor air quality in schools by utilizing displacement ventilation system." Proceedings of Indoor Air 2002. Monterey, California. June 30 - July 5.

Johnston, M. and Davis, J. 2001. "Survey of K-12 education buildings." *HPAC Engineering.* Vol. 73, No. 7: 25-30.

Q. Chen and W. Xu. 1998. "A zero-equation turbulence model for indoor airflow simulation." *Energy and Buildings*. 28(2):137-144.

Schneider, Mark. 2002. "Do School Facilities Affect Academic Outcomes?" National Clearinghouse for Educational Facilities. November. http://www.edfacilities.org/pubs/outcomes.pdf.

Turner, W. 1999. "Advanced Ventilation Design for Commercial, Industrial and Institutional Facilities." *HPAC Engineering.* Vol. 71, No.10: 61-66.