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In-Situ performance of displacement ventilation system in Canadian schools with radiant heating systems

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ABSTRACT

Previous research has shown that stratified ventilation systems (UFAD and DV) work well for regions where buildings require year-round cooling; however there are a growing number of buildings using this approach in Canada, where buildings require heating during winter months. This paper presents results from two field studies conducted in a school equipped with a combination of displacement ventilation and radiant heating system. The results show that the measured contaminant removal effectiveness is better than that predicted in previous studies for heating conditions. In addition, key predictors of thermal comfort are also generally within limits set by ASHRAE standards.

INTRODUCTION

There are two types of mechanical ventilation systems applied to commercial buildings: mixing ventilation and stratified ventilation. In mixing ventilation the air is supplied in such a way that room air is fully mixed and the contaminant concentration is the same in the whole room. In stratified ventilation, a stratified flow is created using the buoyancy forces in the room to entrain and transport the air as well as heat and contaminants from lower levels of the space upward, where they are exhausted at or close to the ceiling. Stratified ventilation systems, underfloor air distribution (UFAD) system and displacement ventilation (DV)), are methods of delivering space conditioning in offices and other commercial buildings that is increasingly being considered as a serious alternative to conventional ceiling-based air distribution systems because of the potential significant benefits that it can provide (Bauman, 2003).

With UFAD and DV systems, conditioned air from the air handling unit (AHU) is delivered to the space through floor diffusers or sidewall diffusers at floor level, many in close proximity to the building occupants. Air is returned at ceiling level. This produces an overall floor-to-ceiling air flow pattern that takes advantage of the natural buoyancy produced by heat sources in the office and more efficiently removes heat loads and contaminants from the space (REHVA, 2002; Bauman, 2003 and Chen, 2003). Stratified air distribution systems are becoming popular for modern buildings because of improved indoor air quality (Chen and Glicksman, 2003; Bauman and Daly, 2003). Some studies (Hu et al., 1999; Im et al., 2005) have reported that the systems are more energy efficient thereby reducing energy demand.

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Many previous studies (Lin et al., 2005; Kobayashi and Chen, 2003; and Yuan et al., 1998) indicate that the design parameters have significant impact on the ventilation and energy performance of stratified air distribution systems. Thus, proper selection of diffusers and ventilation systems is important to the air distribution created by DV and UFAD systems.

The approach presented in ASHRAE Standards 55-2004 and 129-1997 is often used in the literature as the reference method for the assessment of air distribution in rooms. The thermal performance of the air distribution system is assessed using two indices: the Draft rating Index (DR) and the Vertical Air Temperature Difference (VATD), which should be respectively lower than 20% and 3 K. The IAQ performance of the air distribution system is often assessed by using the contaminant removal effectiveness (CRE). CRE characterizes the ability of a system to remove air-borne contaminants.

The revision of Standard 62.1-2007 allows some adjustment in ventilation rates based on the ventilation effectiveness of the air distribution system, a feature that may give credit to UFAD and DV systems. Mixing-type air distribution systems can achieve a well mixed space at best, defined as having ventilation effectiveness of 1.0, as determined in accordance with ASHRAE Standard 129-1997. By definition mixing-type systems cannot provide preferential ventilation ($E_v > 1$), in which some credit could be obtained for improved air change effectiveness at the breathing level in the space. Displacement ventilation systems are known to provide improved ventilation effectiveness in the occupied zone. This performance characteristic is being addressed more specially in the ASHRAE Standard 62.1-2007 in which default values for ventilation effectiveness are recommended for different air distribution system configurations and modes of operation. The recommended values are (1) 1.2 for displacement ventilation system in cooling mode, (2) 0.7 for displacement ventilation system in heating mode, (3) 1.0 for an overhead system in cooling mode, and (4) 0.8 for an overhead system in heating mode. UFAD systems are not explicitly addressed, but it is expected that ventilation effectiveness for UFAD with floor diffusers will be less than or equal to 1.2 but higher than 1.0. As a result of their parametric study ASHRAE Research Project 1373 (Jiang and Chen (RP-1373 2008)) propose various values for air distribution effectiveness. In cooling mode, the CRE with UFAD and DV systems is 1.05 – 1.35 for offices and classrooms. In heating mode, the CRE for the DV and UFAD systems is 0.75 – 1.0 for indoor spaces.

Stratified systems are currently in place in North American buildings and in a situation where systems are being designed and installed at an increasingly rapid pace. However, a full understanding and characterization of some of the most fundamental aspects of these systems performance have yet to be done. There is some data on cooling season, but there is no reported data on their actual performance during the heating season. Previous research ignores the specific characteristics of the Canadian climate: the need to operate in both heating and cooling modes. Further on site research is required to measure the performance of DV in heating mode and assess the impact of a perimeter heating system on the performance of a displacement ventilation system in heating mode. In this paper, two field studies conducted in schools equipped with displacement ventilation systems are presented. Results include the performance of displacement systems in terms of indoor air quality and predicted thermal comfort.

STUDY BUILDINGS

Calmar Elementary School, located in Calmar (south west of the city of Edmonton) as shown in Figure 1, is the first new-build Alberta school to be LEED (Leadership in Energy & Environmental Design) Canada-NC 1.0 accredited. Thomas L. Wells Public School is located in Scarborough (residential suburb area of Toronto) (Figure 1) and it is an award winning school, recognized for its sustainable energy design and is the first "LEED Silver" certified elementary school in Canada.

Calmar Elementary School

The school is a one-story building with a rectangular plan oriented along the East-West axis, with classrooms located in the east and west wings (see Figure 1). The LEED Canada-NC 1.0 accredited school's key sustainability features relevant to indoor environmental quality include: operable windows, displacement ventilation, passive solar control, and daylighting in all occupied spaces. Daylighting is provided by south-facing upper sealed ribbon windows and lower peripheral operable windows. Users have access to light switches, lower peripheral operable windows but not to thermostat control.

The ventilation system is 100% fresh air (100% OA) with a heat recovery wheel) for preheating and pre-cooling of the incoming air. The heat recovery wheel is switched on whenever supply fans are operating and there is a requirement for pre-heating the outside air. The system could also be used in summer to pre-cool outside air with the building air. The air is conditioned through heating coil and then delivered to the space (classrooms and computer room) through sidewall diffusers at floor level. The total airflow to each classroom is based on ASHRAE standard 62.1-2007 (7.5 L/s per occupant) (15.9 ft^3/min per occupant). In heating season, heat is delivered to the spaces (classrooms and computer room) through hot water shelf radiators located at ceiling level over the windows on the perimeter. Air supply to classrooms is delivered through sidewall diffusers located at floor level and return grille located at ceiling level.

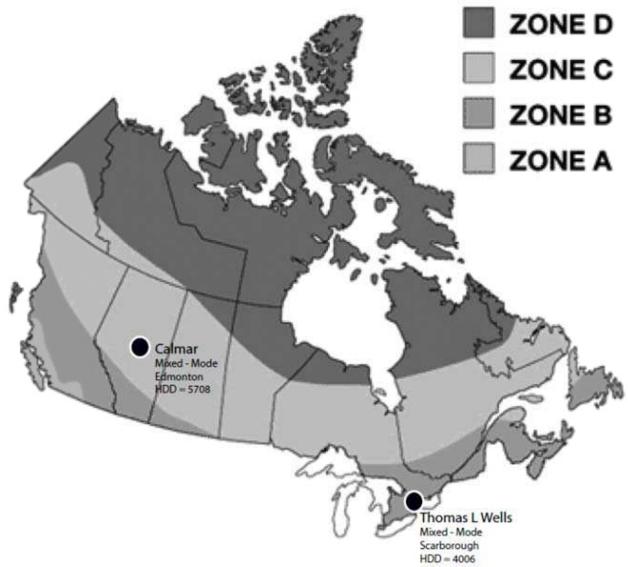

Figure 1. Field Study Location.

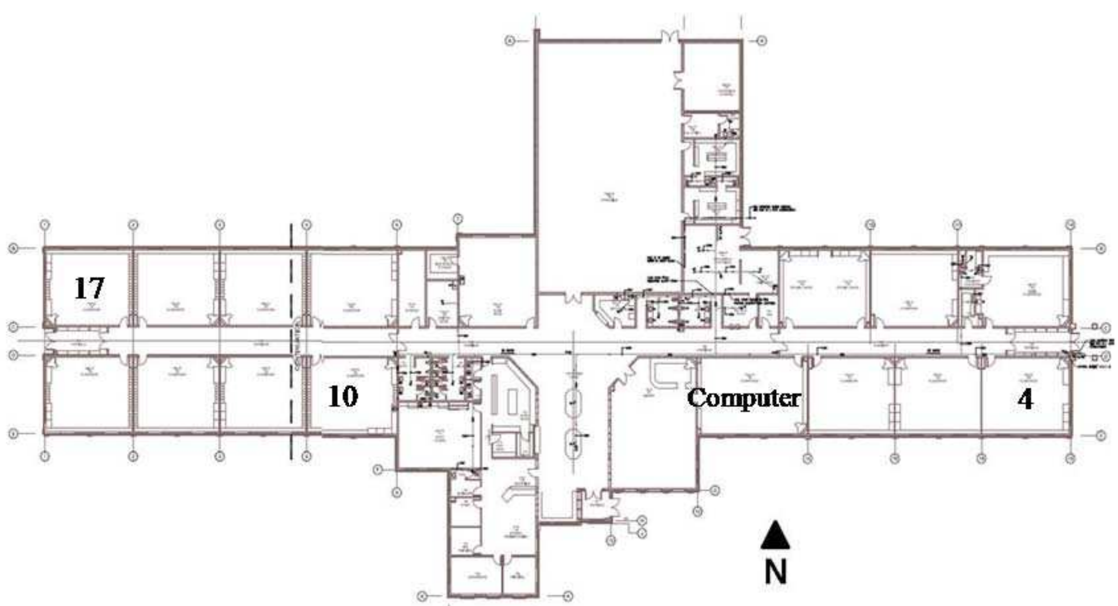

Figure 2. Plan of Calmar School - monitored classrooms (numbered rooms) and computer room.

Thomas L. Wells Public School

The school is a two-storey "H" shaped building oriented along the East-West axis as shown in Figure 3 and has a gross floor area of 5,554 m^2 (59,783 ft^2). The school has a hybrid ventilation system integrating mechanical displacement ventilation and natural ventilation (operable windows). The school's key sustainability features relevant to indoor environmental quality include: operable windows, displacement ventilation, passive solar control, and daylighting in all occupied spaces. Users have access to light switches, On/Off ventilation switch and thermostat. The thermostat setting in classrooms is centrally controlled by the building management system (BMS). Perimeter heating is provided by a hydronic radiant floor system. Mechanical air supply in classrooms is delivered by displacement ventilation through sidewall diffusers located at floor level. Exhaust air diffusers are located in the ceilings.

The school is equipped with VAV displacement ventilation system which consists of two Air Handling Units: AHU 1 for the kindergarten and second floor north and AHU 2 for first floor and second floor south. Figure 3 shows general characteristics of a typical classroom and the design specifications of the mechanical system. The air is conditioned (through a heating coil or cooling coil) and then delivered to the space (classrooms) through sidewall diffusers at floor level. The total airflow to each classroom is typically 234 L/s (495.8 ft^3/min) based on 7.5 L/s (15.9 ft^3/min per occupant) per occupant (ASHRAE standard 62.1-2004). Each classroom has five diffusers installed in the interior wall at floor level. Three returns are installed at the ceiling close to the exterior wall. Supplemental heat delivery to classrooms is achieved through a hydronic radiant floor heating system located on the perimeter. The hydronic system provides heat by warming water to a moderate temperature. The water is then circulated through an underfloor circuit thus warming the floor. Heat is then radiated and convected from the floor to the room and occupants.

Figure 3 Plan of Thomas L. Wells School - monitored classrooms indicated with black points

PROCEDURE

Measurement Schedule

Calmar School - The performance assessment of the DV system at Calmar elementary school was conducted during one day - April 21st, 2009. Measurements were taken in three classrooms and a computer room. The three classrooms and computer room were occupied (students, teacher and teaching assistant) during the measurement period. The room orientation, occupancy, number of measurement locations and outdoor temperature for that day are shown in Table 1. The main differences between the monitored rooms were the room's orientation, occupancy and outdoor temperature which varied from 9.7°C (45.5°F) (early morning) to 21.1°C (70°F) (mid-afternoon), leading to higher supply air temperature in the afternoon.

Table 1. Calmar School – Monitored spaces				
Classroom	17	10	Computer	4
Orientation	North	South	South	South
No. of pupils	17	12	31	15
No. of measurement locations	4	4	3	3
Outdoor temperature - °C (°F)	9.7 (45.5)	14.9 (58.8)	19.1 (66.4)	21.2 (70)

Thomas L. Wells School - The performance assessment of the DV system at Thomas L. Wells Public School consisted of a short monitoring period that took place in four pre-selected classrooms on February 10th 2010. During the period of time specified in Table 2, measurements were taken at three different locations in each classroom, by moving an instrumented pole over sections of floor. Measurement locations were over sections of floor without hydronic radiant heating, over floor with hydronic radiant heating and at the border between the two sections of floor.

Table 2. Thomas L. Wells School - Monitored Spaces				
Classroom	222	232	236	174
Orientation	North	South-West	South	South-East
No. of pupils	28	33	24	20
No. of measurement locations	3	3	3	3
Outdoor temperature - °C (°F)	-7.4 (17.7)	-7.1 (19.2)	-5.4 (22.3)	-4.5 (23.9)

Measurement Procedure

Measurements were carried out in compliance with ASHRAE Standards 113-2005, 129-1997 and 55-2004. Instrumented main pole was used for detailed spatial and vertical characterization of the indoor environment. A return pole was used to measure the air temperature and CO_2 level at the return grilles in the rooms and a reference pole was used to measure the reference air temperature and relative humidity at a height of 1.1 m (0.3 ft) above the floor in the room. The three instrumented poles are part of a monitoring kit, built for the monitoring requirements of this study, and main pole is shown in Figure 4. The accuracy of the sensors was the main concerns (meeting ASHRAE standard specifications) in designing and building the set-up. Sampling from all sensors occurred at an interval of three seconds for a total duration of three minutes and the average of the 60 readings is recorded.

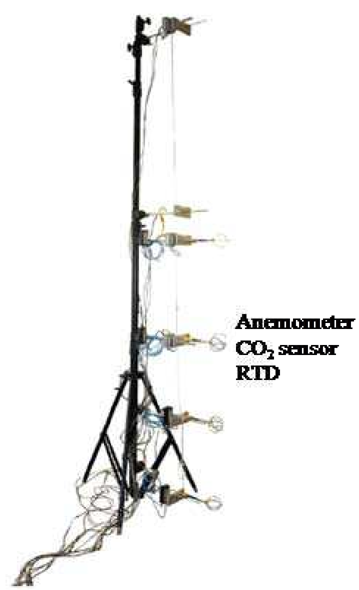

Figure 4. Main measurement pole instrumented with anemometers, CO_2 sensors and RTDs

ANALYSIS

The performance of displacement ventilation systems in Calmar and Thomas L. Wells schools were assessed using three criteria: (1) Predicted thermal comfort – vertical air temperature difference and draft ratio and (2) IAQ – CRE. The following sections detail the measurements and calculations that apply to each of the above evaluation criteria.

Predicted Thermal Comfort

To quantify the extent of thermal stratification and the vertical air temperature difference for a standing and seating person in the occupied spaces, air temperatures were measured at six heights 0.1, 0.6, 1.1, 1.7, 2.2, and 2.8 m (0.3, 2.0, 3.6, 5.6, 7.2 and 9.2 ft) above the floor in the monitored spaces. Measurements were taken at four spatial locations in classrooms 17 and 10 and at three locations in classroom 4 and computer room in Calmar school. According to the ASHRAE standard 55-2004 the temperature difference between the head level (1.7 m (5.6 ft) above the floor for a standing person, 1.1 m (3.6 ft) for a seated person) and the ankle level (0.1 m (0.3 ft) above the floor) should be less than 3°C to be considered acceptable conditions. Displacement-ventilated rooms could present occupant discomfort due to draft, because of air supplied at floor level closer to the occupants. To predict the extent of the thermal discomfort due to draft in the occupied spaces, mean air velocities were measured at four heights 0.1, 0.6, 1.1, and 1.7 m (0.3, 2.0, 3.6 and 5.6 ft) above the floor at different locations within classrooms and computer room. The percentage of people predicted to be dissatisfied due to draft is the Draft Ratio (DR) and should be less than 20%.

Indoor Air Quality

To quantify the indoor air quality two measures of ventilation effectiveness are used: the air contaminant concentration distribution and CRE. CO_2 concentrations were measured at three heights, breathing height of seated and standing person (1.1 m (3.6 ft) and 1.7 m (5.6 ft)), ceiling (2.8 m (9.2 ft)), and diffuser and return grille, respectively. ASHRAE Standard 62.1-2007 suggests an indoor CO_2 concentration limit of outdoor concentration (300-500 ppm) plus 700 ppm, when outdoor air is introduced into the room at the rate of 7.5 L/s per person. CRE indicates the efficiency of the ventilation process in controlling exposures to an indoor-generated contaminant emitted at locations spatially distributed within a building and rooms. It is practical to measure the CO_2 concentrations for CRE calculation, which should be representative of the CRE for other occupant-generated pollutants. Since CO_2 measurements were made at the breathing height of seated and standing adults, for each measurement location within a classrooms two corresponding values of local CRE were calculated, one based on CO_2 measurement at seated breathing height and one based on CO_2 measurements at standing breathing height – both calculations also used CO_2 data from the supply diffuser and return grille.

RESULTS AND DISCUSSION

The field measurements at Calmar school were carried out under spring outdoor conditions with the school HVAC system functioning in a heating mode and the measured air supply temperature at diffusers varied between 20.5^{o}C (68.9°F) and 23.7^{o}C (74.7°F). The field measurements at Thomas L. Wells school were carried out under winter outdoor conditions with the school HVAC system functioning in a heating mode and the measured air supply temperature at diffusers varied between 18^{o}C (64.4°F) and 23^{o}C (73.4°F).

Predicted Thermal Comfort

The average thermal comfort index VATD in all monitored classroom in both schools was lower than the maximum acceptable values of VATD < 3ºC. The average value for each classroom at seating position height (1.1 m) (3.6 ft) and standing position height (1.7 m) (5.6 ft) are presented in Figure 5 for Calmar School and in Figure 6 for Thomas L. Wells School.

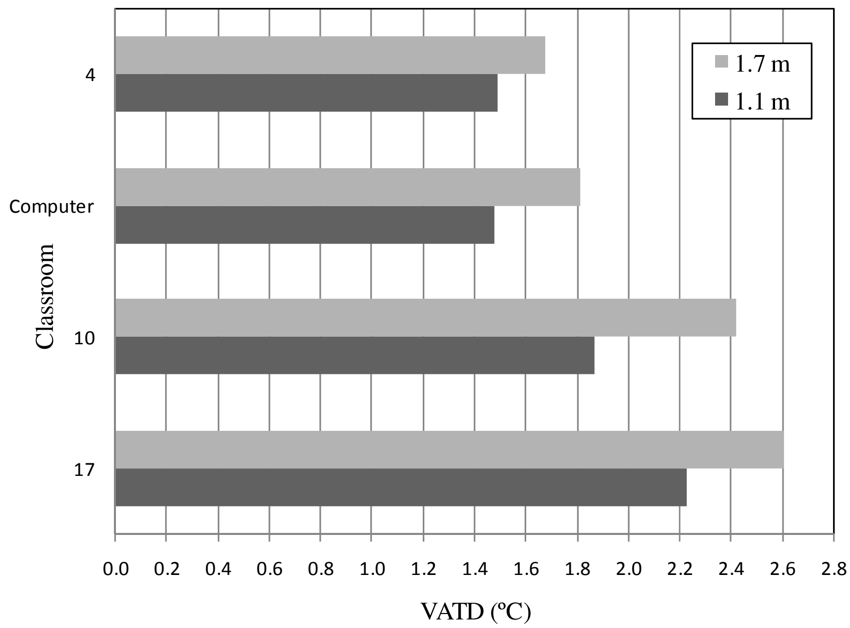

Figure 5. Classroom average VATD at Calmar school

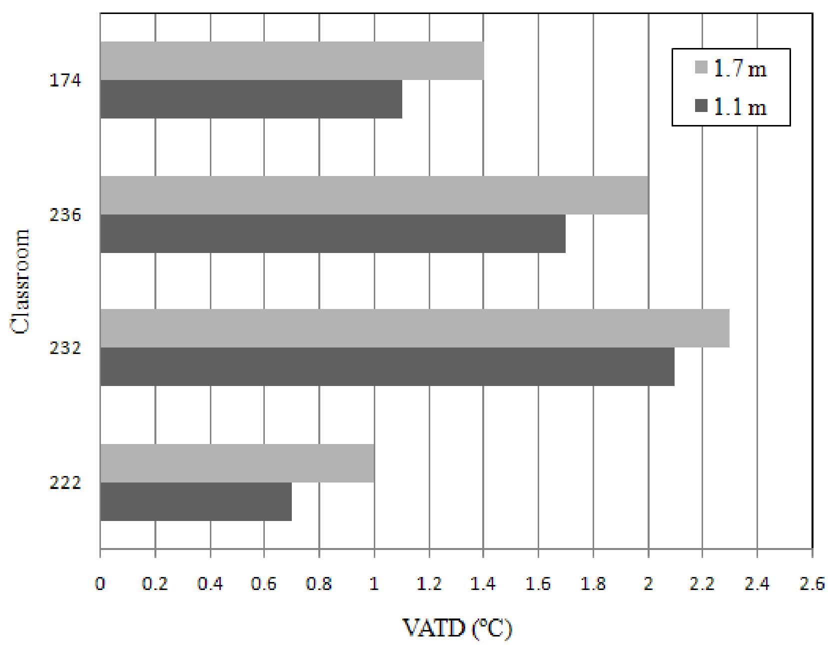

Figure 6. Classroom average VATD at Thomas L. Wells school

The average thermal comfort index DR ranged from 2.1 to 22.3 % at Calmar School (Figure 7). The thermal comfort was not met at 1.7 m (5.6 ft) height in classrooms 17 and 10 where the DR was slightly higher than the maximum acceptable of 20%. The average thermal comfort index DR ranged from 0.1 to 24.1% at Thomas L. Wells School (Figure 8). The thermal comfort due to draft was not met at 1.1 m (3.6 ft) height in classrooms 222, 232 and 236 where the DR was slightly higher than the maximum acceptable of 20%.

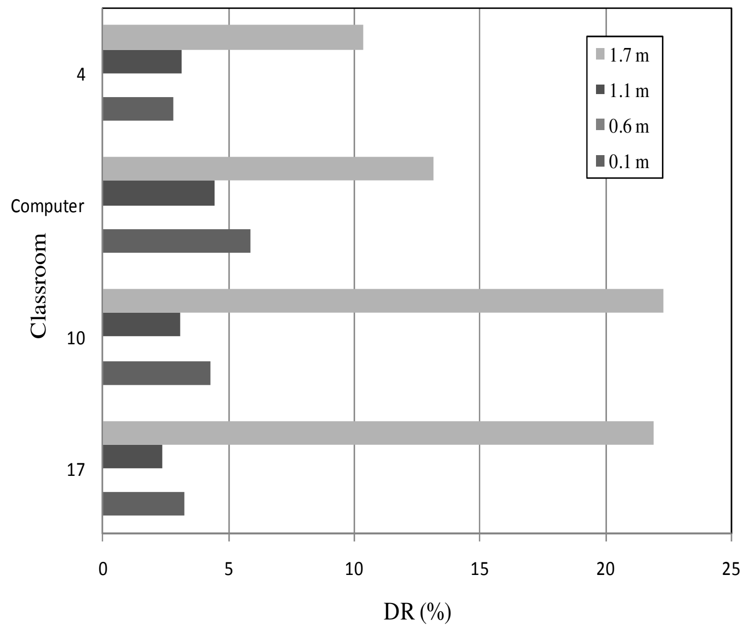

Figure 7. Classroom average DR at Calmar school

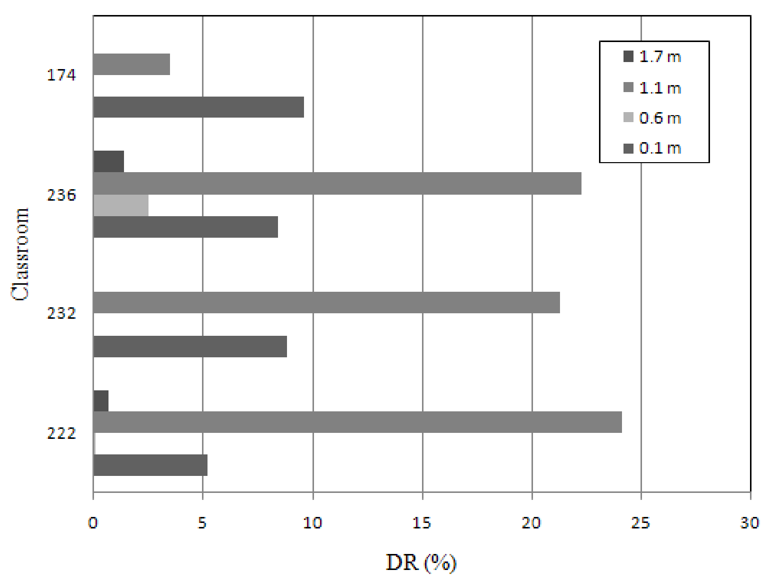

Figure 8. Classroom average DR at Thomas L. Wells school

Indoor Air Quality

The average CRE based on CO_2 measurements at the breathing height of seated adults 1.1 m (3.6 ft), standing adult 1.7 m (5.6 ft) and at the nearby supply diffuser and return grille are presented for both schools in Figure 9 and figure 10. CRE at Calmar School was better than what has been reported for DV systems in heating mode (Jiang et Chen 2008) with the exception of classroom 4. As a result of their parametric study, ASHRAE Research Project 1373 proposes various values for air distribution effectiveness. In cooling mode, the CRE with the UFAD and DV systems is 1.05 – 1.35 for offices and classrooms. In heating mode, the CRE for the DV and UFAD systems was 0.75 – 1.0 for indoor spaces. Classroom 4 monitored in the afternoon was supplied with 100% outdoor air at 23.7 ºC, which demonstrated poor ventilation effectiveness in the occupied zone (CRE<1). The afternoon results do support the findings from the latest ASHRAE Research Project on ventilation effectiveness (Jiang et al. 2008), which state that the CRE index is below 1 during heating mode.

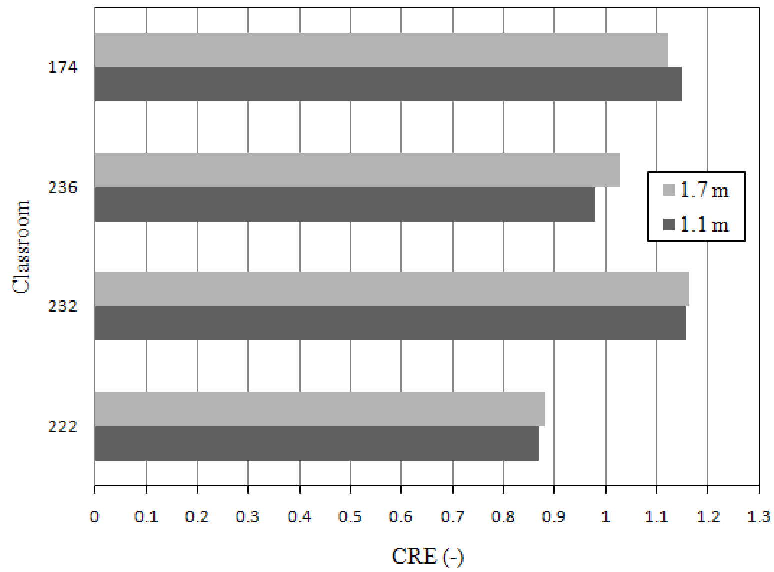

Figure 9. Classroom average CRE at Thomas L. Wells school

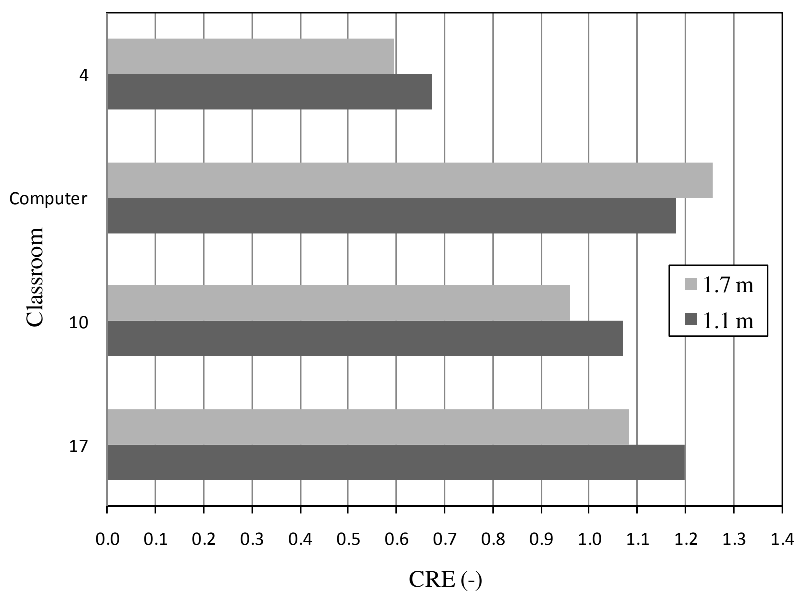

Figure 10. Classroom average CRE at Calmar school

The local average CO_2 concentrations were below 700 ppm above outdoor air level (~450 ppm) in all classrooms and computer room at Calmar School. However, local average concentration of CO_2 was much higher than 700 ppm above outdoor air level (~470 ppm) in all monitored classrooms at Thomas L. Wells School. The outdoor air intake was controlled by CO_2 sensor located in the return duct in the case of Thomas L. Wells School. It was discovered afterwards that the school CO_2 sensor has not been calibrated, which called for the minimum fresh air damper position despite a level of CO_2 concentration way above the threshold imposed by the control strategy.

CONCLUSIONS

In-situ monitoring of thermal parameters was carried out in two schools with displacement ventilation systems in the buildings working in heating mode. The thermal comfort and indoor air quality indices (DR, VATD and CRE) were calculated for up to four measurement locations in classrooms to assess the in-situ performance of the displacement ventilation system. Average vertical air difference temperature index was within acceptable limits of VATD < 3°C in both schools. Calmar School measurements showed that threshold limits with regard to draft were generally not exceeded in the occupied zone (< 1.7 m) (< 5.6 ft); however, thermal comfort was not met at 1.7 m (5.6 ft) in classrooms 10 and 17 due draft issue. Thomas L. Wells presented an acceptable thermal comfort except at height of 1.1 m (3.6 ft) in Classrooms 236, 232 and 222, when DR was used as the criteria for assessment. The local average CO_2 concentrations were below 700 ppm above outdoor air level (~450 ppm) in all classrooms and computer room at Calmar School. However, local average concentration of CO_2 was much higher than 700 ppm above outdoor air level (~470 ppm) in all monitored classrooms at Thomas L. Wells School.

With the exception of Classroom 4, Classrooms (17 and 10) and Computer room at Calmar School provide a satisfactory indoor environment in term of air quality index with average CRE > 1. Measured CRE at Thomas L. Wells School ranged from 0.87 to 1.16. The air quality index (CRE) with the exception of classroom 4 (Calmar school) was better than what is usually reported in heating mode for TDV system. These results contradict the latest ASHRAE Research Project on ventilation effectiveness (Jiang et Chen 2008), which states that the CRE index is below 1 during heating mode and equals to 0.7 as recommended by ASHRAE standard 62.1-2007. Even with secondary heating, the results of their study for classrooms showed that the TDV system does not perform as well as during cooling mode. The results from these two field studies, where the ventilation systems were in a heating mode with fairly low supply temperatures, do not support these findings and showed good performance of a displacement ventilation system in heating mode. However, the afternoon results in the case of classroom 4 at Calmar School with high supply temperature do support these findings and showed bad performance of a displacement ventilation system characterized by CRE<1. One explanation can be that the high supply air temperature could affect the distribution of contaminant in the space and produce a non-stratification distribution.

ACKNOWLEDGEMENTS

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