INDOOR ENVIRONMENT OF A CLASSROOM IN A PASSIVE SCHOOL BUILDING WITH DISPLACEMENT VENTILATION

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ABSTRACT

Indoor air quality and thermal comfort of the passive school buildings should be particularly paid more attentions due to those new passive school buildings adopted highly airtight building envelopes. In this study indoor environment of a very densely occupied classroom with displacement ventilation has been investigated. In order to appropriately model the classroom, all the simulation parameters are based on a typical real classroom structure, its air tightness and infiltration rate were measured. CFD (Computational Fluid Dynamics) simulations were then performed for a typical summer day in Munich in the accordingly modelled classroom. Representative thermal comfort parameters e.g. vertical temperature difference between ankle and head, and percentage of dissatisfied etc. have been analyzed and evaluated.

The results obtained show that the displacement ventilation in the present work could provide generally favourable human thermal comfort and at the same time guarantee high indoor air quality indicated by the CO_2 concentration in the occupant regions. Numerical results demonstrate that promotion of mechanical ventilation rate can simultaneously enhance the dilution of indoor air pollutants and the non-uniformity of indoor pollutant distributions.

Moreover, those results derived from the spatially and temporally resolved 3D distributions of the indoor air temperature and CO_2 concentration, respectively, can help find the appropriate locations in the classroom for a single temperature and CO_2 sensor inside the classroom to representatively measure the indoor air temperature and CO_2 concentration in a long running term.

INTRODUCTION

The school building is a very densely populated place. High thermal comfort and indoor air quality can actually have a positive influence not only on students' health but also can improve learning and teaching such as understanding of concepts, abilities of problem solving, and attitudes towards learning etc (Puteh, et al. 2012). Therefore, it is quite necessary that there is a fine indoor environment for learning and teaching in schools. In order to obtain healthy and comfortable indoor air environment in classrooms, school buildings usually have been operated with high energy cost. The passive houses have been introduced into the practical operations appropriately three decades ago, where the buildings that requires significantly little energy for apace heating or cooling. However, there were many researches and experiences on the passive residential buildings but almost nothing has been done in school buildings (Feist et al. 2005, Chel et al. 2009).

Nowadays, world energy crisis and carbon emission have brought heavy pressures on the building energy reductions, especially on those high energy consumption buildings (Liu et al. 2010). Recently, the passive school buildings were initiated in Germany, where super high level insulations, energy efficient windows, super low air infiltration as well as mechanical heating/cooling recovery ventilation systems were simultaneously applied.

Since there are the crowded living and learning environment in school buildings, some studies estimate that more than 50% of school children have some kinds of allergy and asthma (T. Karimipanah et al. 2007). Hence, for the new-built passive school buildings with the super low air infiltration, indoor air quality and thermal comfort should be particularly paid more attentions.

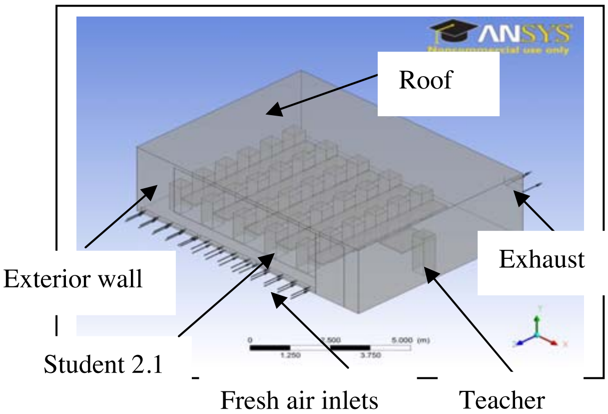
In this study, a typical classroom in a passive school building will be firstly selected, where displacement ventilation unit has been put into operations. Displacement ventilation is room energy efficient air delivery and distribution strategy where conditioned and fresh outdoor air is supplied at floor level, warmer and polluted by occupants indoor air is then extracted above the occupied zone. Due to such advantages, displacement ventilation is well suited for improving indoor air quality in the occupied zones. On the other hand, displacement ventilation may be a cause of discomfort due to large vertical temperature differences and drafts (Yuan et al. 1998). Therefore, it is very important for us to investigate thermal comfort of occupants in the passive school building with displacement ventilation.

EXPERIMENT

Physical model

A typical classroom with its dimensions 9.77 m (length) x 7.25 m (width) x 3 m (height) was extracted from one of passive school building situated in the region of southern Germany, as illustrated in Figure 1 (a). The classroom has been modelled as a rectangular parallelepiped enclosure by the software package ANSYS/CFX (ANSYS 2012), as shown in Figure 1 (b). The classroom totally accommodates 30 students, who are distributed in 5 lines and 6 rows and 1.20 m in height. In addition, one teacher is 1.70 m in height and standing before the students and 6 slender tables. All occupants were described by the hexagonal shapes in the research model.

(a) Passive school building in Bavaria, Germany



(b) Model classroom extracted from the passive school building

Figure 1 Façade picture of passive school building and the geometry of the modelled classroom, where all the occupants (student and teacher) were simplified into cuboids and the symbol Student 2.1 represents that the student sits at Line 2 and Row 1.

The objective classroom is located in the top floor, such that the roof and front wall both expose to the surrounding environment. On the front wall, there is a large window sizing of 6.25 m × 2.10 m and an entrance with 1.25 m × 2.85 m. As such low energy school building, external walls are composed of interior plaster, reinforced concrete, and heat insulation, whereas the roof is formed by the reinforced concrete and heat insulation. Insulation material of WLG 035 is applied in the wall insulation layers, and triple level glasses (from UNIGLAS corporation) are adopted for the windows, such that heat transfer coefficients (U-values) of the classroom envelopes are maintained at lower values, i.e., front wall (external wall) 0.128 W/m^2K, other vertical walls (interior walls) 4.357 W/m^2K, floor 2.450 W/m^2K, roof 0.095 W/m^2K, and window 0.870 W/m^2K.

There are three diffusers of same size (2.50 m × 0.15 m) which are installed side by side in the lower part of the front wall (beneath the window and immediately 0.10 m above the floor) and they horizontally discharge fresh and cold air into the space. On the backward side opposing to the front wall, the exhausting port sizing of 0.825 m × 0.325 m was positioned in the high altitude and lying just 0.60 m below the ceiling. With such arrangement, displacement ventilation then will be established, i.e., fresh and cold air will be supplied by the diffusers into the classroom and spread along the floor; after being heated and polluted by the indoor occupants, it will become warm and travels upward to the top exhaust.

The blower door testing and air change rates

Air leakage is usually regarded as one of the main causes of energy loss. For this passive school building, the performance of air tightness has been on-site measured by the use of blower door methodology (Sherman 1995). The blower door is actually a machine used to measure the air-tightness of small to medium size buildings. Here, the air changes per hour at a specified building pressure at 50 Pa were defined, i.e.,

$$ACH_{50} = \frac{Q_{50}}{V_{classroom}} \quad (1)$$

This metric indicates the rate at which the air in a building or enclosure is replaced with outside air, and as a result, is an important metric in determinations of indoor air quality (Sherman 1995). While these blower door testing efforts were useful identifying leakage pathways and in accounting for otherwise inexplicable energy losses, the results could not be used to determine real time air exchange in buildings under natural ventilation, i.e., infiltrations. Which here was determined by the estimation model developed by Kronvall and Persily (Sherman 1987), formulated as follows,

$$ACH_{k-p} \equiv \frac{ACH_{50}}{20} \quad (2)$$

With our measurements, $ACH_{50} =$ 0.17 h^{-1} based on the Standard EN ISO 9972 (ISO EN 9972 2006), and $ACH_{K\text{-}P} =$ 0.01 h^{-1} were then determined. ACH_{50} is normally used as an indicator of air leakage or energy losses for the room/building. Therfore, it illustrates this school building with tiny air infiltration rate can obviously reduce energy losses due to air leakage.

SIMULATION

Thermal boundary conditions

Based on EN ISO 7730 (ISO EN 7730 2005), a seated student can produce about 75 W heat gains, a standing teacher can generate about 100 W heat gains. According to Chen 2004 (Chen et al. 2004), for the displacement ventilation, the convective and radiative ratio should be assumed by 80/20 for occupants, therefore, it can be calculated that the convective heat gains are 60 W and 80 W, respectively, for a seated student and a standing teacher. The convective heat in this study is assumed to be uniformly distributed on the entire surface of the heated objects.

In a typical summer day, ambient environment averaged temperature was 30 °C in Munich. Solar radiation from windows was almost avoided with the shading system outside the windows. As the displacement ventilation system was operated, the supplying fresh air through those diffusers was maintained at 17 °C, being lower than indoor air average temperature levels.

Mathematical modelling and CFD methodologies

The Computational Fluid Dynamics (CFD) software package ANSYS/CFX is used to simulate air flow, heat transfer and airborne contaminant concentrations and solves the governing flow equations (ANSYS 2012). It can predict the important parameters of building thermal environment and indoor air quality e.g. air temperature, air velocity and CO_2 concentration etc. with high spatial and temporal resolution. Shear stress transport turbulence model (SST k- ω : k is turbulent kinetic energy; ω is specific dissipation) was adopted to account for the turbulent buoyancy effects and near wall turbulence shear transitions (Bartosiewicz et al. 2006). In order to meet reasonable convergence of the model, the Root Mean Square (RMS) residuals for mass and momentum equations were taken as 0.01%, whereas overall conservation target of energy and species was set to 1% (Zhao et al. 2008, Wang et al. 2012, Zhao et al. 2012).

The grid independence solutions test was tried with series of 127551, 381588, and 452270 nodes inside the enclosure. 3D average air temperature was almost unchanged (25.2 °C) after 381588 nodes were implemented, for the typical steady flow situation with fresh air ventilation rate maintained at 660 m^3/h. Therefore, grid system of 381588 nodes will be adopted in our subsequent researches.

CFD simulation results validated by representative on-site measurement

In order to demonstrate the credibility of CFD simulation, it is necessary to validate the CFD program before it was extensively adopted as a tool of study. The validation was done by comparing the CFD results with experimental data obtained by the on-site measurement.

On the place of student 2.1, five thermocouples were perpendicularly distributed along the vertical lines. The error for measuring temperature by the thermocouples was ±0.4^{0}C. Shown in Figure 2, the temperature gradient in the lower part of the room was much larger than that in the upper part, thus relatively large discrepancies between CFD values and measurements were observed in the lower levels. Nevertheless, the computed temperatures agree with the measured data within 1.4 ^{0}C, which can convince the reliability of the subsequent numerical investigations.

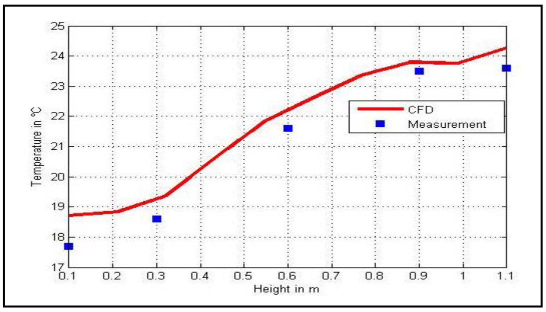


Figure 2 Comparisons between CFD modelling results and measurements from thermocouples distributed along vertical lines at one sampling location, i.e., student 2.1.

DISCUSSION AND RESULT ANALYSIS

Steady airflow and thermal comfort

The airflow motions in the classroom distributed by the installed displacement ventilation system focus on creating a comfortable thermal environment. There are a number of thermal comfort parameters in the research fields such as percentage of dissatisfied (*PD*) and temperature difference between ankle and head etc. which will be used in this study as thermal comfort criteria (Noh et al. 2007).

As this ventilation unit was put into use, fresh air of ventilation rate 660 m^3/h from the diffusers was usually maintained and supplied into the enclosure, to meet the air volume requirement of each occupant 20 m^3/h in Germany. Subsequently, steady airflow and thermal dispersion will be established with such displacement ventilation system.

Seen from Figure 3 (a), the first row students' feet near the inlets are directly subjected to room air with very low temperature (approximately 18 °C), being far lower than those of regions where other students seated. As the fresh air spreads forward, classroom heating objectives will gradually improve its temperature level. Around the floor region of third row, air temperatures are observed higher than 21 °C; as air arrives to the region of row six, its temperature approaches 24 °C. Observing from Figure 3 (b), horizontal plane elevated 1.10 m from the floor, air temperatures in the majority of students occupation area are higher than 24 °C. This can demonstrate that the displacement ventilation flow pattern will result in the vertical thermal stratification.

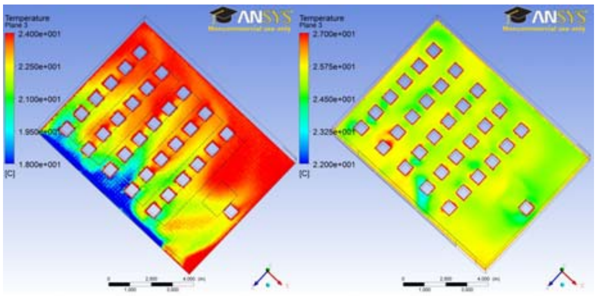


Figure 3 Spatial distributions of air temperatures across horizontal sections respectively at elevating height of 0.10 m (left (a): Isothermal distributions on the horizontal plane vertically elevated at 0.10 m) and 1.10 m (right (b): Isothermal distributions on the horizontal plane vertically elevated at 1.10 m), both immediately from the floor.

Actually, vertical air temperature difference between head and ankles ($\Delta t_{a,v}$) can be put into the formulation of percentage of dissatisfied (Yuan et al. 1998, Chen et al. 2009),

$$PD = \frac{100\%}{1+\exp\left(5.76-0.856\cdot\Delta t_{a,v}\right)} \qquad (3)$$

Here should be noted that, the height difference between head and ankle is 1.10 m – 0.10 m, while that becomes 1.70 m – 0.10 m for that standing teacher (ISO EN 7730 2005). Particularly, formulation is only suitable for $\Delta t_{a,v}$ < 8 °C due to it was derived from the original data using logistic regression analysis.

General correlations between *PD* and vertical air temperature difference are plotted in Figure 4, where one observes that *PD* will exponentially increase with the vertical air temperature difference. As expected, occupants will have better human thermal comfort with lower values of vertical temperature difference. Actually, continuously decreasing vertical temperature difference will reduce the thermal stratification sensitivity of occupants, which has been represented by the values of *PD*. Some sampling locations and data are summarized in Table 1, including the temperature of head and ankle positions, head to ankle temperature difference as well as percentage of dissatisfied. Observing from the table, vertical temperature difference at students 2.1 and 2.2 significantly exceed the permitted value (3 °C), such that their *PD* values are higher than other locations. Therefore, the students should take seats a bit far from the fresh air inlets, in order to improve their thermal comfort. With this rule, the first row students near the inlets should move to the positions of between second and third row a little e.g. 0.2 m, the rest of students should be distributed uniformly in the rest of space. Actually, they do not feel thermal discomfort after the moving. Or the inlet air temperature should be higher a little e.g. 18 °C or 19 °C so as to enhance their thermal comfort.

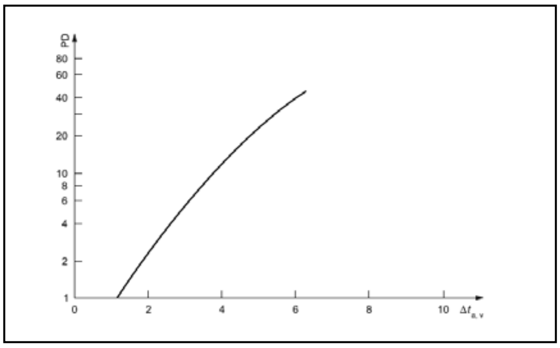


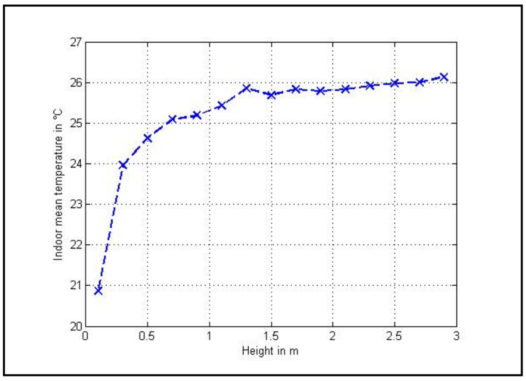
Figure 4 Comfort parameter PD as a function of vertical air temperature difference.

Table 1
Vertical temperature levels from head to ankle as well as Percentage of Dissatisfied at some sampling locations around the Teacher and Students

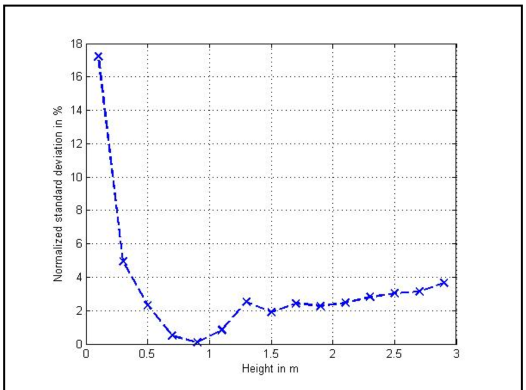
Location	**Ankle** °C	**Head** °C	**Vertical difference** °C	***PD*** %
Teacher	22.8	25.8	3.0	4.0
Student 2.1	18.7	24.3	5.6	27.5
Student 2.2	21.8	26.3	4.5	12.9
Student 2.3	23.4	26.5	3.1	4.3
Student 2.4	23.4	26.1	2.7	3.1
Student 2.5	23.3	26.1	2.8	3.3
Student 2.6	23.6	25.8	2.2	2.0

Cross section averaged temperatures at some elevated horizontal planes, from 0.10 m to 2.90 m, are illustrated in Figure 5 (a). With such displacement ventilation, the vertical thermal stratification mainly occurs at the altitude below approximately 1.50 m, which heavily influences the thermal comfort of occupants. This also explains why the students' rows near the supplying air inlets have relatively high values of *PD*. Further modifications and optimizations of this displacement ventilation system should be implemented.

In order to clearly disclose the thermal stratification characteristics by the plane averaged temperatures and 3D average temperature, as plotted in Figure 5 (b), the normalized standard deviations of the horizontal cross section plane averaged air temperatures are obtained by the normalization with the enclosure 3D average air temperature (25.2 °C). Observing from Figure 5 (b), the highest deviation (approximately 17%) is achieved at the elevation of 0.10 m, where classroom diffusers deliver cool and fresh air across the lower region with cold air sinking down to the floor. With the increasing elevation of horizontal planes, the standard deviation decreases sharply toward to zero as the vertical elevation achieves at 0.90 m immediately above the floor, where average temperature is very close to the classroom volume averaged temperature 25.2°C. Below this critical plane elevated at 0.90 m, air temperatures are lower than volume averaged temperature; whereas, above that critical plane, air temperatures exceed the volume averaged one, and their deviations increase a little, asymptotically approaching 4%. This is due to the fact that upper regions of this classroom tend to be of uniform isotherms, which favourably produces the thermal buffers to reduce the heat transfer rates between surroundings and building ceilings. This observation has been made by the past researches of displacement ventilation (Yuan et al. 1999). Furthermore, as the classroom air temperatures should be monitored by a single thermocouple or a thermal sensor for the future energy cost evaluation of the whole low energy school building, it should be directly put inside the bottom half region of the classroom (vertically elevated at 0.90 m) shifting aside from diffusers towards the outlet, to represent the average temperature level of the whole classroom.



(a) Cross horizontal plane mean temperatures



(b) Normalized standard deviation of the horizontal plane averaged temperatures

Figure 5 Horizontal plane averaged temperatures and their normalized standard deviations as functions of their vertical elevations in the classroom with stable displacement ventilation rate 660 m^3/h

CO_2 emissions and ventilation control procedures

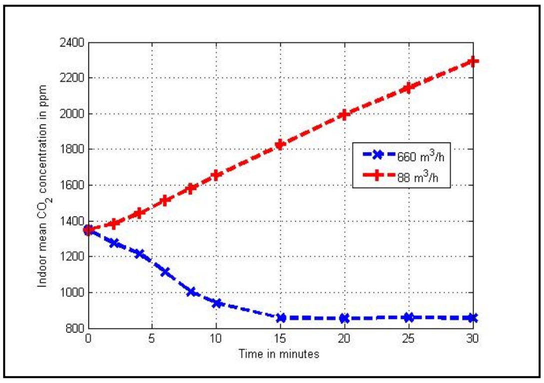
Indoor air quality (IAQ) is also an important factor for evaluating the performance of the ventilated classrooms (Yu et al. 2011, Liu et al. 2012). The classroom CO_2 concentration was generally measured higher due to the air-tightness materials and low ventilation rates as well as highly dense occupants of passive school buildings. Therefore, indoor CO_2 concentration will be used as an indicator of IAQ in the present investigation.

Generally, each occupant in the classroom generates about 20 liters per hour of pure CO_2 due to respiration, and their total contributions will significantly increase overall CO_2 concentration levels in such classroom of low air infiltration ($ACH_{K\text{-}P}$ = 0.01 h^{-1}). One can easily estimate that room averaged CO_2 concentration will exponentially increase up to 1000 ppm after 15 minutes, if there were no any dilution by entraining ambient fresh air.

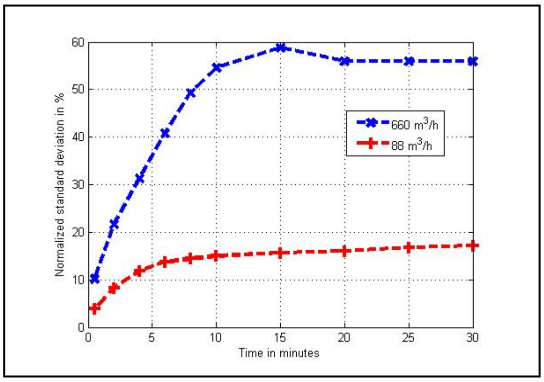
Now, momentum and thermal boundary conditions implemented in the above steady thermal flow simulations were maintained in the following transient simulations. With the same initial volume averaged CO_2 concentration 1350 ppm, two different levels of mechanical ventilation rates were respectively implemented, 660 m^3/h and 88 m^3/h. As illustrated in Figure 6, temporary evolutions of indoor mean CO_2 concentration and its normalized standard deviation are plotted as the functions of time, respectively shown in Figure 6 (a) and 6 (b). Observing from Figure 6 (a), for the case of high ventilation rate, indoor mean CO_2 level decays rapidly due to the quantity of fresh air entrained into the room is far higher than the CO_2 production from the crowded occupants. But, after 15 minutes, decaying rate of this curve tends to be flat due to the entraining fresh air gradually dilutes the room in a whole level. On the other hand, the curve represented by the case of low ventilation rate shows the pollutant concentration almost linearly increases with time. Actually, this is due to the CO_2 production rate of occupants far exceeds that fresh air dilution rate of low ventilation rate. In contrast, mechanical ventilation of high level ventilation rate can quickly dilute the room air (within 10 minutes) into less polluted level (less than 900 ppm). Therefore, promotion of mechanical ventilation rate can directly contribute to the quick dilution of indoor air pollutants, and too low ventilation rate could not effectively inhibit the increase of indoor CO_2 concentration levels.

Mechanically supplying air not only quickly dilutes indoor air, but also causes the non-uniform distributions of pollutants. Non-uniformity of CO_2 dispersions can be essentially represented by the values of normalized standard deviations of pollutant concentration shown in Figure 6 (b). For the case of high ventilation rate, dilution of indoor CO_2 could be implemented within several minutes, but the non-uniformity of indoor pollutant distributions increases greatly, achieving maximum of 59% just after 15 minutes. Thereafter fresh air was continuously entrained into the room, both pollutant concentration levels and its spatial non-uniformity decrease. For the case of low ventilation rate, the pollutant levels always increase with time and the non-uniformity of pollutant distribution increases slightly, being up to 18% after 30 minutes. Physically, the fresh air delivered by low ventilation rate will gradually penetrate into the room mixtures, which will not drastically and suddenly change the original distributions of pollutants.

In addition to the supplying flow momentum, the displacement ventilation flow pattern can result in a sensible species boundary layer in the lower region of this classroom. Observing from Figure 7, the spatial distributions of pollutants are significantly divided by the pollution layer, where the CO_2 concentration difference between upper and lower sides is greater than 300 ppm. This also can explain its peak values of standard deviations shown in Figure 6.



(a) Volume averaged concentration of indoor CO_2



(b) Standard deviation of volume-averaged CO_2 concentration

Figure 6 Temporary evolutions of indoor mean CO_2 concentration (a) and its normalized standard deviation (b) inside the classroom with two different levels of mechanical ventilation rates and same initial pollutant concentrations, i.e., 660 m^3/h and 1350 ppm (Blue line), and 88 m^3/h and 1350 ppm (Red line)

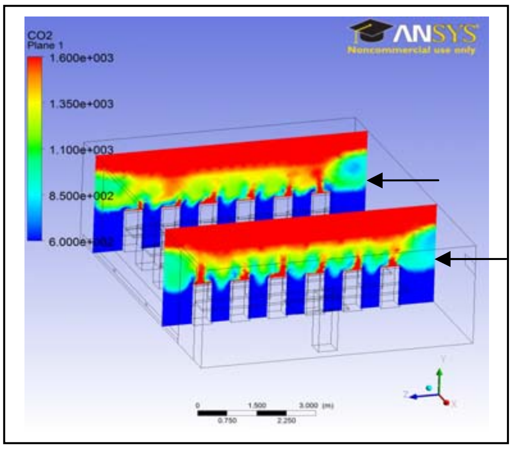


Figure 7 Spatial distributions of CO_2 concentration at the time instant 15 minutes with mechanical ventilation rate 660 m^3/h and initial classroom CO_2 level of 1350 ppm

Species stratification is also observed in the displacement ventilation classroom shown in Figure 7. With such stratification, pollutants almost could not take long residence in the occupant regions (vertical altitude less than 2.0 m), whereas they will gradually accumulate in the upper regions toward the ceiling, where local CO_2 concentration is far higher than 1000 ppm near the ceiling. Therefore, the appropriate installation location for a CO_2 sensor should be in the upper region of this classroom (as indicated by the black arrows in Figure 7), where local species concentration can represent the volume-averaged concentration level (Wang et al. 2012). With such installations, the whole pollutant emissions across this passive building could be monitored in the long running time.

CONCLUSION

Indoor environment including thermal comfort and indoor air quality of one representative classroom in a passive school building has been experimentally and numerically investigated in the present work. Displacement ventilation unit was put into operation with high airtight building envelopes, which aim to reduce the building heat transfer losses and improve energy efficiency.

Steady air flow and thermal dispersion in one typical summer day was numerically simulated by the CFD methodology. Displacement ventilation thermal stratification has been demonstrated by the spatial thermal distributions and their normalized standard deviations. Sharp thermal gradients were observed below 0.90 m, whereas uniform isotherms present in the upper regions, where the thermal buffers to reduce the heat transfer rates between surroundings and building ceilings.

Representative thermal comfort parameters, percentage of dissatisfied, and temperature difference between ankle and head have been evaluated. Rows of students adjacent to the diffusers will be subjected to high values of percentage of dissatisfied and steep thermal gradients between their ankle and head.

Following that, indoor air quality indicated by the CO_2 concentration was investigated in terms of two different mechanical ventilation rates. Temporary evolutions of indoor mean CO_2 concentration indicate that promotion of mechanical ventilation rate can directly contribute to the quick dilution of indoor air pollutants. Normalized standard deviations of temporary pollutant concentrations clearly illuminate that non-uniformity of indoor pollutant distributions increases with the mechanical ventilation rate. The fresh air delivered by low ventilation rate will gradually penetrate into the room mixtures, which will not drastically change the original distributions of pollutants.

Sensible species boundary layer and species stratification have been observed in the process of displacement ventilation in this classroom. With such stratification, pollutants almost could not stay in the occupant regions (vertically lower than 2.0 m), whereas they will gradually accumulate in the upper regions toward the ceiling.

Present research and findings derived from our CFD simulations could help such passive school building designers and operators to determine the suitable arrangements of school occupants and the appropriate locations in the classroom for observing indoor mean temperature and CO_2 concentration in a long running term.

NOMENCLATURE

ACH_{50} = the air changes per hour at 50 Pascal (h^{-1})
Q_{50} = airflow rate at 50 Pascal (m^3/h)
$V_{classroom}$ = the volume of this classroom (m^3)
$ACH_{K\text{-}P}$ = the average infiltration rate (h^{-1})
$\Delta t_{a,v}$ = t_{head} - t_{ankle} (°C)

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