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CFD simulations of thermal comfort for naturally ventilated school buildings

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CFD simulations of thermal comfort for naturally ventilated school buildings

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Abstract. A comfortable learning and teaching environment is one of the key concerns in the design of school buildings. In Singapore public school buildings, most of classrooms are naturally ventilated, for the sake of energy saving and sustainable design. It is necessary to study the impact of environmental conditions and design features to get some clues to facilitate the designers for naturally ventilated school designs. In this study, CFD simulations have been carried out to evaluate the natural ventilation condition of the classrooms and identify the plausible reasons causing thermal discomfort for an actual school in Singapore. The CFD approach adopted in this study is closely in reference to the CFD methodology outlined in Green Mark 2015 for Non Residential Building from Building and Construction Authority (BCA), subject to the four prevailing wind conditions available in Singapore. Meanwhile, some mitigation measures including the removal of incline roofs have been explored in order to enhance the natural ventilation for those classrooms. In addition, thermal comfort analyses have been performed with simulations including ceiling fans and heat loads. CFD simulations demonstrate that classrooms at higher levels experience weaker cross ventilation than those at lower levels for the three prevailing wind conditions from the north, northeast and south, respectively. This may due mainly to the fact that the school resides within the wake zone of the surrounding buildings. The flow directions across the classrooms of concern are found to be opposite to the prevailing wind direction under the three prevailing wind conditions. Thermally uncomfortable conditions in the classrooms at higher levels are well simulated and captured using the proposed thermal comfort analyses. All the observations match well with the feedback from the school. Besides, scenario-based studies with regard to plausible mitigation measures have shed the lights towards enhanced natural ventilation across the classrooms of the school of concern.

1. Introduction

In Singapore, there are about 350 public schools providing learning environments for more than 400,000 students [1], i.e., almost 10% of the total population of Singapore are in school buildings. A safe, thermally comfortable and conductive environment is necessary needed for optimal functioning of school buildings. In addition, student advocacy is the one of the key driving forces for sustainability. Recently, positive energy school design is advocated in Singapore. For a positive energy school, it produces more on-site renewable energy than it consumes on an annual basis [2]. This renewable energy can be from the solar panels installed for the school buildings.

To achieve a positive energy school, a variety of energy saving and sustainable designs are adopted. Maximizing the natural ventilation for school buildings is one of the ways to save energy. Generally, most classrooms in Singapore public schools are designed to be naturally ventilated, while air-conditioning is used in special purpose classrooms and staff offices. Natural ventilation takes advantage of natural wind to move air in and out of the classrooms. The performance of natural ventilation across classrooms is highly dependent on the environmental conditions including prevailing wind conditions and blockage of surrounding buildings as well as the architectural design features of the school buildings. It is necessary to study the impact of environmental conditions and design features to get some clues to facilitate optimization of naturally ventilated school designs. Computational Fluid Dynamics (CFD) is an ideal tool to study the impact of various conditions and features, not only to save cost and time, but also to provide full three-dimensional field data for better understanding of building performance [3].

In Singapore, regional guidelines about CFD methodology for natural ventilation simulations have been established and detailed in Building and Construction Authority (BCA) Green Mark 2015 for Non Residential Buildings (NRB). In this project, our CFD simulations closely reference the methodology documented in the above Green Mark code.

The project aims to identify the optimized layout and potential strategies to harness natural ventilation to achieve desirable thermal comfort for classrooms. In this paper, we present our findings for the first school, which is currently facing thermal discomfort issues for some classrooms. We evaluate the natural ventilation condition of the classrooms and identify the plausible reasons causing the thermal discomfort. Meanwhile, we also explore some mitigation measures to enhance the natural ventilation for those classrooms.

2. CFD Methodology

The CFD simulations in this study includes two segments. We first evaluate the cross ventilation of the classrooms under natural ventilation driven solely by wind. As the wind velocities within the classrooms are too small to satisfy the minimum velocity prerequisites for the corresponding BCA Green Mark ratings, thermal comfort analysis is performed with simulations including ceiling fans and heat loads.

2.1. Computational domain

The school itself is modeled based on as-built CAD drawings. The school includes ten blocks, where the classrooms of concern are located at Block A and B, as shown in Figure 1. Block A is a four-storey building, with an incline roof (with an angle of 45° from horizontal) from Level 3 to Level 1. Block B is a three-storey building, with an incline roof from top to Level 1.

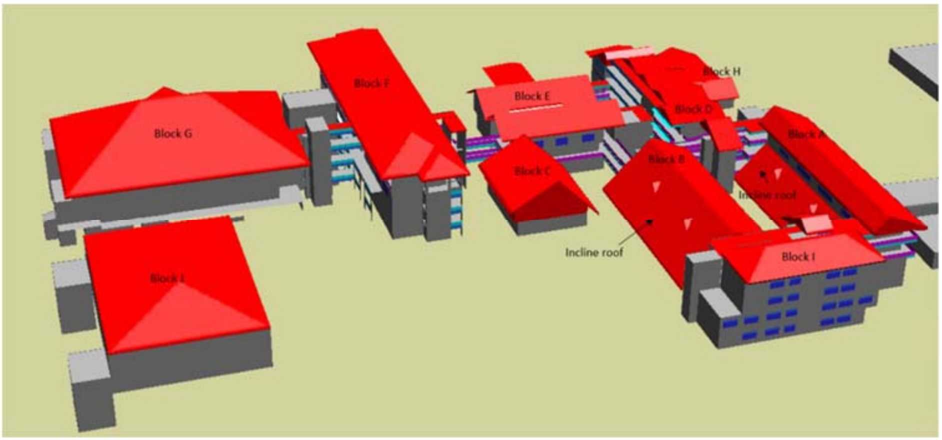

Figure 1. School buildings modeled in ANSYS

In the study, surrounding buildings within 500 m distance from the school have been modelled explicitly, as shown in Figure 2(a). The school and surrounding buildings are assumed to be located on a flat ground because the terrain elevation differs by no more than 10 m height. Site survey shows that

Level 1 of the surrounding high-rise residential buildings adjacent to the school are mostly occupied by stalls/shops, a kindergarten and walls, which do not allow wind to pass through them. Thus, the assumption that the surrounding buildings are without open voids deck areas at ground level as modeled in our CFD simulations is representative.

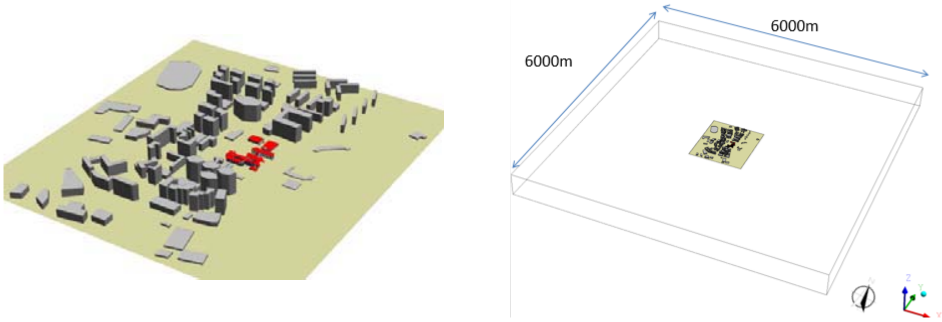

Figure 2 3D models (left) and the computational domain (right) for simulating the ventilation condition across the school buildings.

2.2. *Ceiling fans and heat loads*

For the thermal comfort assessment using Predicted Mean Vote (PMV) equation, the simulation models include the ceiling fans and heat loads for each naturally ventilated classroom. Generally, there are six ceiling fans in each classroom. Each ceiling fan is represented by a cylinder with a diameter of 1.5m and height of 0.25m. Fixed velocity profiles are applied to each fan cylinder. The fans are assumed to have similar velocity profiles as the ceiling fan FM131H-W reported by Y. Momoi. et al [4].

As advised by school management, there are 40 persons per typical classroom of 90 m^2 approximately. A sensible heat load of 70 W/person is adopted in the simulation [5]. The typical equipment heat load in the classroom is the lighting heat load, which is assumed to be 12 W/m^2 according to the floor area. Solar heat load is calculated by the solar ray tracing model in ANSYS Fluent.

2.3. *Boundary conditions*

The inbound vertical wind profile is assumed to be given by the Logarithmic Law using the following equations [6]:

$$U(z) = \frac{u^*_{ABL}}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \quad (1)$$

$$k(z) = \frac{(u^*_{ABL})^2}{\sqrt{C_\mu}} \quad (2)$$

$$\varepsilon(z) = \frac{(u^*_{ABL})^3}{\kappa(z+z_0)} \quad (3)$$

where $u^*_{ABL} = \kappa U_{ref}/\ln[(h_{ref}+z_0)/z_0]$, is the friction velocity, κ represents von Karman Constant (0.42), C_μ is the turbulence constant (0.09), $z_0$is the aerodynamic roughness length and U_{ref} is the reference velocity measured at the reference height h_{ref}. The reference velocity is based on 18-year meteorological data in Singapore at a reference height of 15.0 m as in Table 1.

Pressure outlet conditions are imposed on the leeward-side domain boundary. Non-slip wall boundary conditions are applied to all the wall surfaces. Ambient air temperature is assumed to be 30°C. Occupant heat load is assumed to be uniformly imposed at the classroom floor area. It is assumed that 20% of lighting heat load is uniformly imposed at the ceiling area, while 80% of lighting heat load is uniformly imposed at the floor and wall area of each classroom.

Table 1. Four prevailing wind conditions in Singapore (unit: m/s)

Wind direction	Mean Velocity
North	2.0
North-East	2.9
South	2.8
South-East	3.2

2.4. Numerical settings

The simulations are performed using ANSYS Fluent (v17.2), a well-known commercial CFD package. Fluent Meshing is used to generate the hexahedra dominated cutcell mesh for the whole domain, with a total number around 23 million cells. Steady state simulations for incompressible flow are carried out. The realizable k-ε model with standard wall functions is adopted to deal with turbulence. 2nd-order discretization schemes for partial differential terms and SIMPLE solution procedure for algebraic solvers are chosen in the simulations.

3. Results and discussion

3.1. Natural ventilation driven by wind

3.1.1. Urban wind conditions around the school. Four CFD models corresponding to four prevailing wind conditions in Singapore, have been carried out for the school. The CFD results show that the high-rise surrounding buildings at northern, southern and western sides of the school significantly affect the natural wind approaching the school buildings.

Figure 3 displays the vector plot of air velocity at the horizontal cutting plane of 12m above ground and the vector plots on a vertical cutting plane across Block A and Block B under the prevailing wind from the north. The tall buildings around the school create a kind of cavity flow effect. The school is situated in the wake zone where vortexes exist. The air flow direction across the classrooms of BLK A & B is from south to north, which is opposite to the prevailing wind condition. Similar findings can be observed under northeast and south prevailing wind conditions. In contrast, this does not occur for the southeast wind condition. Wind can effectively reach BLK A directly from southeast direction, because there is no blockage with no surrounding buildings on the southeast side of the school.

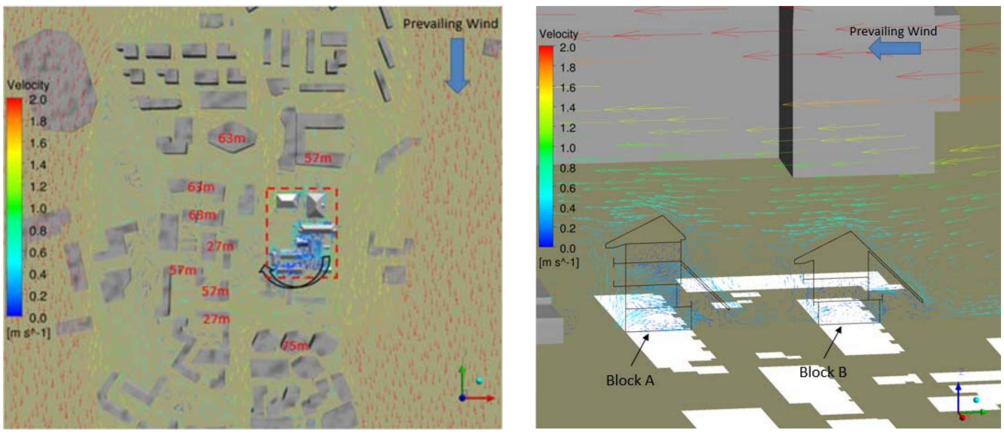

Figure 3. Velocity vector plots on a horizontal cutting plane (left) and a vertical cutting plane (right) across the school (in red dotted box) subject to the prevailing wind from the north.

Table 2 show the average velocity at 1.2m above floor level for each classroom in BLK A. Generally, the wind velocities across the classrooms are relatively low. The average velocity at higher level is smaller than lower levels under the north, northeast and south wind conditions. The observations match well with the feedback from the school that higher levels are currently experiencing worse thermal discomfort.

Table 2. Area-weighted averaged velocity magnitude at the horizontal cutting plane of 1.2m above floor level (unit: m/s)

Location	Prevailing wind direction				Average velocity
Block A	**North**	**Northeast**	**South**	**Southeast**	
Level 1	0.14	0.31	0.23	0.39	0.27
Level 2	0.13	0.29	0.27	0.46	0.29
Level 3	0.12	0.25	0.17	0.65	0.30
Level 4	0.06	0.17	0.18	0.82	0.30
Average	0.11	0.25	0.21	0.57	0.29

3.1.2. Impact of incline roofs. One option is that the incline roofs may significantly block the cross ventilation. To assess the impact, another set of four CFD models with removal of the incline roofs have been carried out. The results show that the average wind velocities across the classrooms in BLK A & BLK B increase by about 0.039m/s ~ 0.049m/s (17%~19.5%). The removal of inclined roofs does not give significant improvement in natural ventilation conditions across classrooms of concern. The poor ventilation conditions occurring in the school are attributed to the site constraints, i.e. the blockage of densely packed surrounding buildings on the vicinities of the school's northern, southern and western sides.

3.1.3. Mitigation measures. Since poorer ventilation is found to occur in classrooms on Level 4 of Block A, the following mitigation measures are proposed to improve the natural ventilation conditions: (1) extend the window height from 1.2m to 1.7m, (2) change the parapet walls along the corridor to railings to reduce the blockage of wind. The results show that the average wind velocity increases about 0.084m/s (28%) with the enlarged window opening, and 0.095m/s (31%) if both mitigation measures are applied.

3.2. Natural ventilation including ceiling fans and heat loads
According to BCA GM 2015 for NRB, the horizontal cutting plane at 1.2m above the finished floor level of the classroom is selected for evaluation of thermal comfort in the naturally ventilated spaces. Table 3 lists the area-weighted average velocities calculated at 1.2m above floor of each classroom in BLK A. In comparison to values in Table 2, the air velocities within the classrooms increase more than double for the north, northeast and south prevailing wind condition. The air speed in the classroom is dominated by the ceiling fans when they are in operation.

Table 3. Area-weighted averaged velocity magnitude at the horizontal cutting plane at 1.2m above floor for NV including ceiling fans and heat loads (unit: m/s)

Location	Prevailing wind direction				Average velocity
Block A	**North**	**Northeast**	**South**	**Southeast**	
Level 1	0.57	0.61	0.61	0.68	0.62
Level 2	0.51	0.53	0.55	0.68	0.57
Level 3	0.50	0.50	0.54	0.63	0.55
Level 4	0.51	0.52	0.59	0.76	0.59
Average	0.53	0.54	0.58	0.69	0.59

With reference to BCA GM 2015 for NRB, a new PMV formula to assess the thermal comfort conditions in natural ventilated classrooms for the Singapore climate has been developed based on on-site measurements and surveys. The PMV formula takes the following form [7]

$$PMV = -6.805 + 0.267 * DBT - 0.87 * WIND \quad (4)$$

where DBT and WIND is indoor dry-bulb temperature (°C) and wind velocity (m/s) at 1.2 m height above the floor, respectively. To meet the thermal comfort requirements for naturally ventilated classrooms in tropical climate, it is expected PMV should take the value of $-1.0 \leq PMV \leq 1.0$ for GM Gold^{PLUS} award and $-0.8 \leq PMV \leq 0.8$ for GM Platinum award.

The resultant PMV values of each classroom are tabulated in Table 4. From the table, we can find that the classrooms at Level 2-4 are thermally warm, i.e. PMV > 1.0, except under southeast prevailing wind condition when the cross natural ventilation is good. This indicates that if the cross ventilation is not strong, heat may be trapped/recirculated within the classroom, although the ceiling fans are in operation. In addition, we can also observe that Level 3 (PMV = 1.9) and Level 4 (PMV = 2.4) under north wind condition and Level 4 (PMV = 2.3) under south wind condition are much worse than other situations. As shown in Figure 4, the air exhaust from the classrooms at Level 2 will rise and be trapped under the incline roof at the upper corner when the wind is not strong enough for cross ventilation at Level 3. The warm air then flows into the classrooms at Level 3 as the replacement air, which contributes to a higher temperature for classrooms at Level 3 relative to Level 2. For Level 4, the hot incline roof due to solar irradiation warms to air flowing into the classrooms through the windows above the incline roof. The makeup air is about 3°C higher than the ambient air temperature (30°C), which results in a room temperature at Level 4 as high as 36°C. Similar phenomena is also observed at Level 4 under south prevailing wind condition, as shown in Figure 5. For northeast and southeast wind conditions, the flash air flows into the classrooms at Level 4 from the south side windows adjacent to the corridors, hence the room temperature is lower.

Table 4. Area-weighted PMV at 1.2m above floor

Location	Prevailing wind direction				Average
Block A	**North**	**Northeast**	**South**	**Southeast**	**PMV**
Level 1	1.0	0.9	1.0	0.8	0.9
Level 2	1.2	1.0	1.2	0.8	1.0
Level 3	1.9	1.0	1.3	0.9	1.3
Level 4	2.4	1.2	2.3	0.8	1.7
Average	1.6	1.0	1.4	0.8	1.2

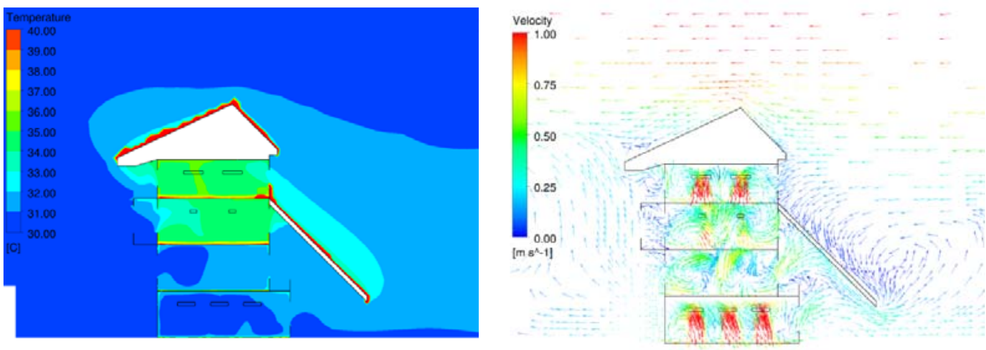

Figure 4. Plots of temperature contours (left) and velocity vector (right) on a vertical cutting plane across the classrooms of BLK A, subject to the prevailing wind from the North.

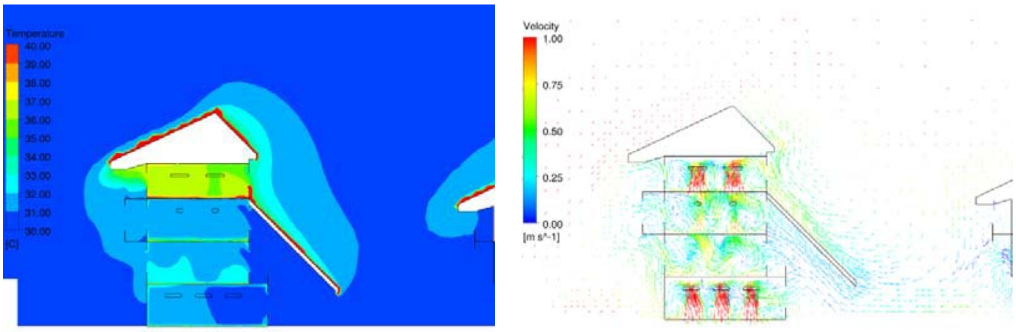

Figure 5. Plots of temperature contours (left) and velocity vector (right) on a vertical cutting plane across the classrooms of BLK A, subject to the prevailing wind from the South.

4. Conclusions

CFD simulations have been carried out to assess the natural ventilation conditions and identify the plausible reasons for thermal discomfort in the naturally ventilated classrooms in a school. The simulation results match well with the feedback from the school side. Based on the results, it is found that surrounding buildings on the vicinity of the school strongly impact the wind flow across the school. School resides within the wake zone and the flow direction across the classrooms of concern is opposite to the prevailing wind direction under north, northeast or south wind conditions. Higher levels suffer weaker cross ventilation than lower levels for these three prevailing wind conditions. Besides, it is found that the inclined roofs, unique architectural features for the school of concern, trap the heat and subsequently increase the room temperature at Level 3, when the cross ventilation is not strong. In addition, warm air, heated by the hot inclined roofs due to solar irradiation, may flow into the Level 4 classrooms through the windows above the inclined roofs, resulting in a much higher room temperature at Level 4. These thermally uncomfortable conditions can be improved, as the inclined roofs are removed, though the removal of inclined roofs does not give significant augmentation in the average velocity across the classrooms. In addition, two mitigation measures to improve the cross ventilation have been studied. Enlarging the window opening shows more effective improvement than changing the parapet walls to railings in this case. As the project is still on-going, additional measures will be explored to improve the thermal comfort within the classrooms, for example, the introduction of directional fans to enhance the horizontal air movement and to exhaust the heat out of the classrooms.

5. References

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