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Utilizing Computational Fluid Dynamics in the Analysis of Natural Ventilation in Buildings

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Abstract**—**Increasing urbanisation has driven building designers to incorporate natural ventilation in the designs of sustainable buildings. This project utilises Computational Fluid Dynamics (CFD) to investigate the natural ventilation of an academic building, SIT@SP, using an assessment criterion based on daily mean temperature and mean velocity. The areas of interest are the pedestrian level of first and fourth levels of the building. A reference case recommended by the Architectural Institute of Japan was used to validate the simulation model. The validated simulation model was then used for coupled simulations on SIT@SP and neighbouring geometries, under two wind speeds. Both steady and transient simulations were used to identify differences in results. Steady and transient results are agreeable with the transient simulation identifying peak velocities during flow development. Under a lower wind speed, the first level was sufficiently ventilated while the fourth level was not. The first level has excessive wind velocities in the higher wind speed and the fourth level was adequately ventilated. Fourth level flow velocity was consistently lower than those of the first level. This is attributed to either simulation model error or poor building design. SIT@SP is concluded to have a sufficiently ventilated first level and insufficiently ventilated fourth level. Future works for this project extend to modifying the urban geometry, simulation model improvements, evaluation using other assessment metrics and extending the area of interest to the entire building.

Keywords**—**Buildings, CFD simulation, natural ventilation, urban airflow.

I. Introduction

VENTILATION refers to using airflow to create a comfortable environment and air quality defined by parameters such as thermal comfort, temperature distribution, humidity and air speed. Managing ventilation performance in buildings can be done through mechanical ventilation devices such as air-conditioners and fans or natural ventilation methods such as adjustable windows and wind catchers.

Increasing pollution and climate change has driven building designers and urban planners to consider sustainable and energy efficient buildings or features [1]-[3]. While it is possible to use photovoltaic panels to reduce the power drawn from electrical grids by generating clean energy on-site, reducing the energy consumption of the building is just as important and more affordable [4]. Use of natural ventilation provides significant energy savings [5] compared to the straightforward option of installing mechanical ventilation devices.

Natural ventilation provides solutions to the problems encountered by the building occupants regarding mechanical ventilation, which are noise, energy consumption, routine maintenance requirements and health problems [2]. Proper integration of natural ventilation in building designs can provide a more comfortable environment [6]. Furthermore, studies [7] shows that use of centralised Heating, Ventilating and Air-Conditioning (HVAC) systems have fine-tuned occupants to expect thermal comfort in a narrow range of temperatures and uniformity. On the other hand, occupants of building with natural ventilation are more tolerant of a wide range of temperatures [1], [5], [7]. However, there are several challenges in the study and evaluation of natural ventilation. Being "natural" ventilation means the flow behaviour is inherently random, complex and dynamic [2], [5]. As such, it would be difficult to achieve efficient control on the flow within the building [2]. The use of natural ventilation is also limited by the external surrounding factors such as noise and air pollution [8].

II. Methodology

A. Software

Simulation for this analysis is conducted using commercial software ANSYS Fluent 14.5 with Academic Teaching Advanced License. Computer Aided Design (CAD) models are created using either ANSYS Design Modeller or Solidworks 2014 depending on model complexity.

B. Simulation Model Validation

Using a case recommended by the Architectural Institute of Japan (AIJ) [9], the urban geometry, shown in Fig 1, is replicated using ANSYS Design Modeler, and simulation conducted by using ANSYS Fluent. The results obtained are then compared with the reference results to determine if the simulation model used is valid. This removes the requirement for full-scale or reduced-scale experiments to determine the accuracy of the simulation model.

In the reference case, the area of interest is the pedestrian level wind around the central block. Air velocity results taken at the measuring points spread throughout the area of interest is normalized as wind speed ratio (by using the inlet velocity).

The wind speed ratio variation across the measuring points is then shown in a graph.

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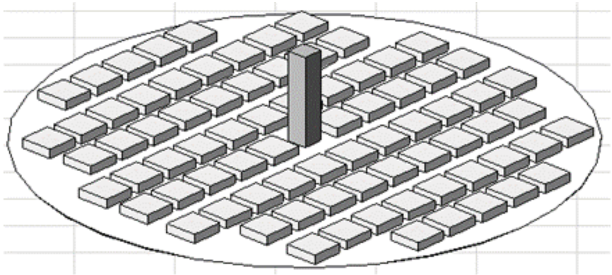

Fig. 1 Reference case geometry

C. Urban Geometry Modeling

The target building for analysis is the Singapore Institute of Technology (SIT) building, SIT@SP. The building has six above-ground levels with naturally ventilated corridors, atrium and stairwells. This standalone building is located within the Singapore Polytechnic campus. Since neighbouring geometries can have a significant effect on the airflow around the target building [9]-[11], buildings up to 250 m from the target building will be included in the simulation.

D. Assessment Criterion

Assessment of ventilation is highly subjective as the level of comfort and tolerance for each individual differs. Several assessment metrics have been proposed for evaluation of ventilation from adaptive thermal metrics proposed by Baker and Standeven [12], air velocities [13]-[15], pressure coefficients [16], pollutant exchange rate [17] and a mixture of parameters such as relative humidity, temperature and carbon dioxide levels [18]. In this analysis, the assessment criterion will be based on the mean velocity and mean temperature [5], shown in Table I.

TABLE I
ASSESSMENT CRITERA BASED ON DAILY MEAN TEMPERATURE AND MEAN VELOCITY, V_M

Daily Mean Temperature (°C)	<10	10 - 25	>25
Vm range causing thermal discomfort due to insufficient wind speed	-	-	<0.7m/s
Vm range for acceptable wind environment	<1.3m/s	<1.5m/s	0.7-1.7m/s
Transition range for Vm from acceptable to strong wind	1.3-2.0m/s	1.5-2.3m/s	1.7-2.9m/s
Vm range causing strong wind-induced discomfort	>2.0m/s	>2.3m/s	>2.9m/s

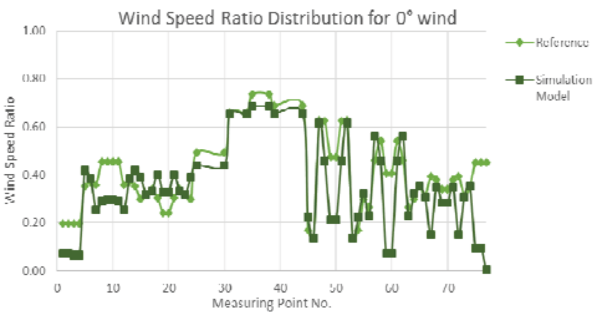

Fig. 2 Comparison Simulation model and Reference results

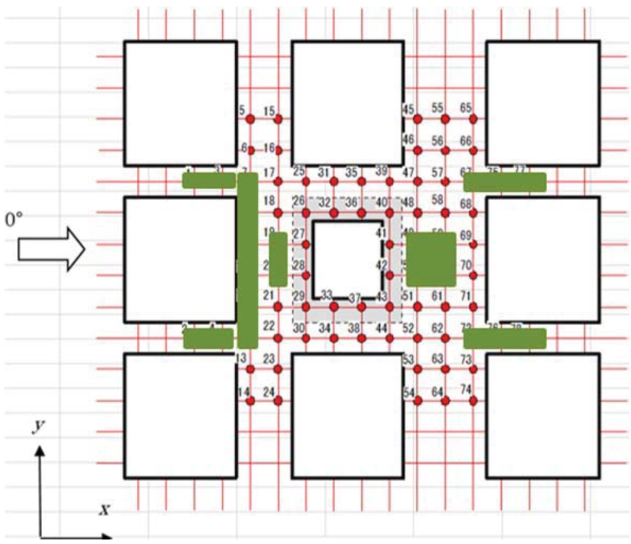

Fig. 3 Highlighted error areas

E. Area of Interest

The first level naturally has the highest pedestrian traffic while the fourth level is approximately half way of the building height. Hence, the area of interest is defined to the pedestrian level wind on the first and fourth level main atrium.

F. Simulation

Wind direction and velocities are naturally difficult to predict, therefore, the yearly mean velocity of 2m/s from the East will be used for the simulation. In addition, gust condition representing the uncommon high wind velocity of 7m/s from the East will also be simulated. The simulation will also be conducted for both steady and transient states. Since natural wind is intrinsically an unstable and oscillating phenomenon, steady state simulations are expected to yield oscillating results. A transient study will be used to explore if there is a significant difference with the steady state results.

III. SIMULATION MODEL VALIDATION

The simulation model results have sufficiently matched the reference results shown in Fig. 2, although there are certain measuring points where the difference in results are significant. These measuring points are noted in Fig. 3 as areas likely to produce erroneous results in the actual simulation. Generally, the model fails to predict the velocity at along-wind, channeled flow areas and behind obstructions.

IV. STEADY SIMULATION: 2M/S

From Table II, both first and fourth levels are insufficiently ventilated as the daily mean temperature in Singapore is well above 25 °C. The lack of wind speed is more pronounced on the fourth level where the velocity is approximately 71% lower than the acceptable whereas the first level is approximately 14% lower. On the first level, the air enters through openings on the top and right of the Fig 4 and exits from the left and bottom. Hence, the flow moves across the atrium and is able to ventilate most of the atrium. For the fourth level, the flow appears to originate from the left and top of Fig. 5 and leaving through the bottom. The majority of the flow does not move towards the openings but rather recirculate within the atrium.

TABLE II
COMPARISON OF 2 M/S STEADY SIMULATION

Location	Simulation mean velocity (m/s)	Acceptable mean velocity (m/s)
Level 1	0.6052	0.7 to 1.7
Level 4	0.2160	

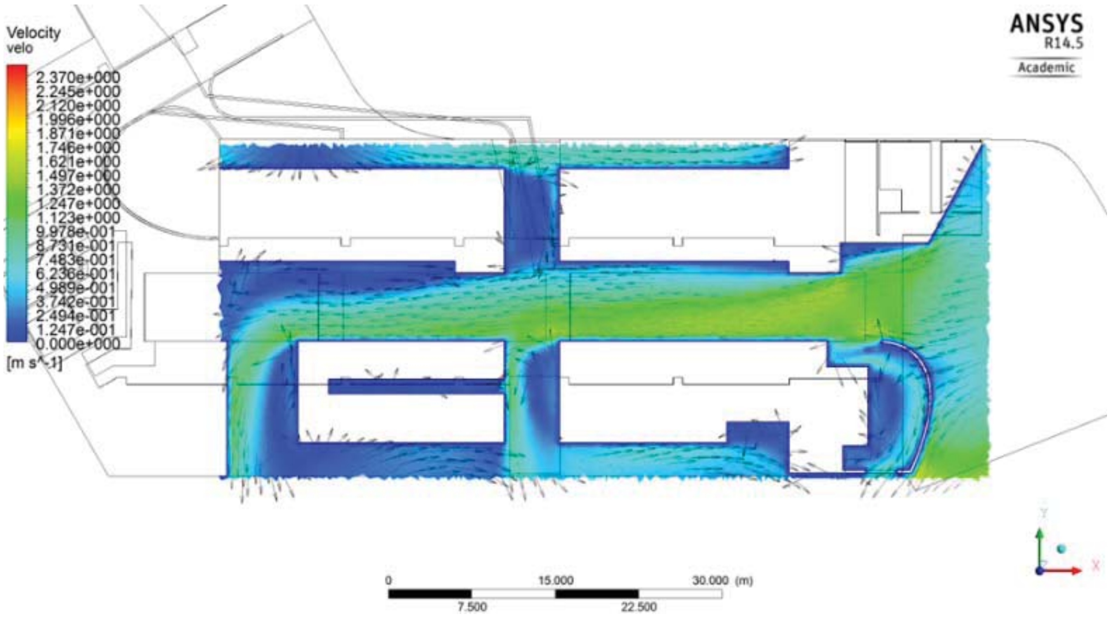

Fig. 4 First level flow field results (2 m/s)

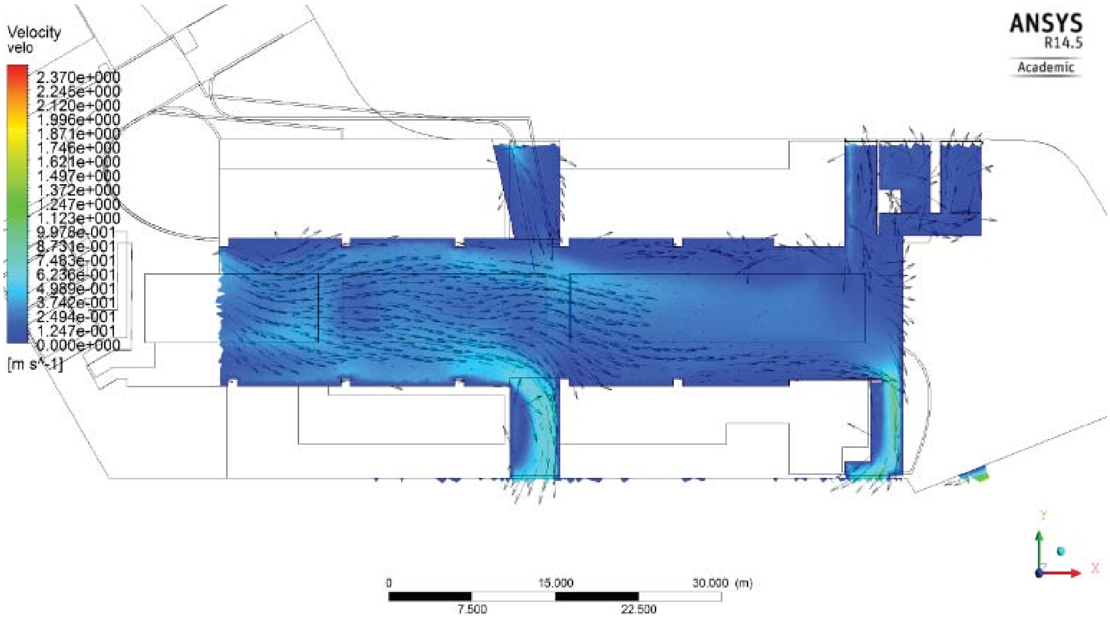

Fig. 5 Fourth level flow field results (2 m/s)

V. TRANSIENT SIMULATION: 2 M/S

Using results at 0.5s intervals, the mean velocity at the areas of interest are listed in Table III. It is evident that mean velocity decreases as time increases. This agrees with the steady state results where time value is infinite. Therefore, the mean velocity would gradually converge towards the steady state results.

TABLE III
SIMULATION MEAN VELOCITY AT VARIOUS TIME (2 M/S)

Time (s)	Mean Velocity (m/s)	
	Level 1	Level 4
0.0	1.820	1.849
0.5	1.432	0.9684
1.0	1.399	0.8899
1.5	1.373	0.8277
2.0	1.350	0.7747
2.5	1.328	0.7290
3.0	1.309	0.6881
3.5	1.292	0.6509
4.0	1.277	0.6168
4.5	1.263	0.5850

VI. STEADY SIMULATION: 7 M/S

Results shown in Table IV suggest that during 7m/s winds, the first level would be subject to mean velocities in the transition range. The fourth level would be within the acceptable mean velocity range. Hence, in 7m/s conditions, the areas of interest would be sufficiently ventilated. However, the first level velocity may cause slight discomfort to some pedestrians as the mean velocity is within the transition range. The airflow movement on both levels, shown in Figs. 6 and 7, are similar to those of the 2m/s wind condition.

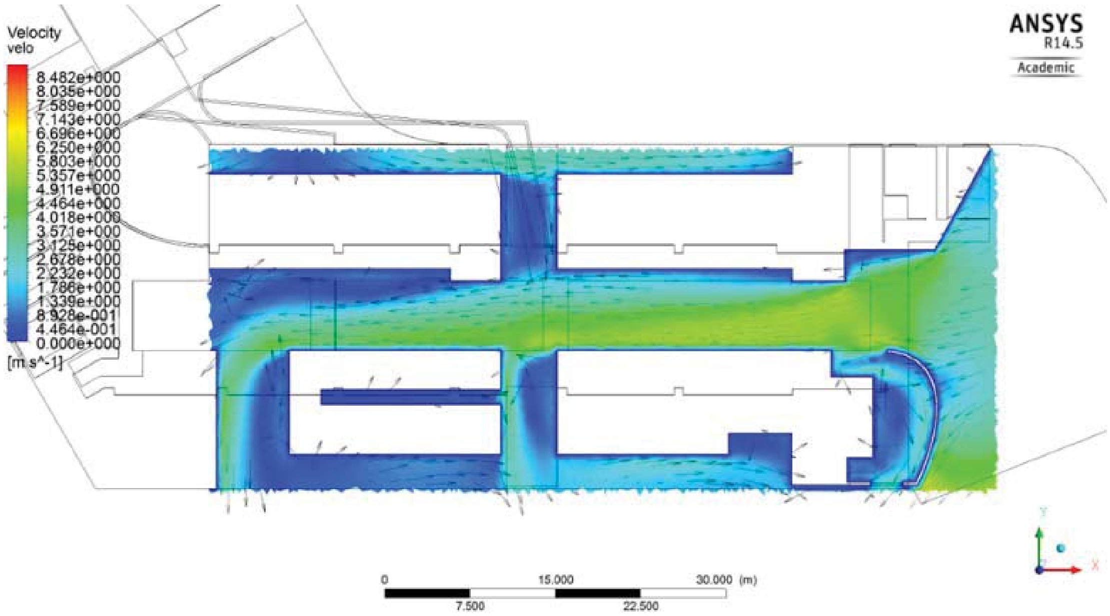

Fig. 6 First level flow field results (7 m/s)

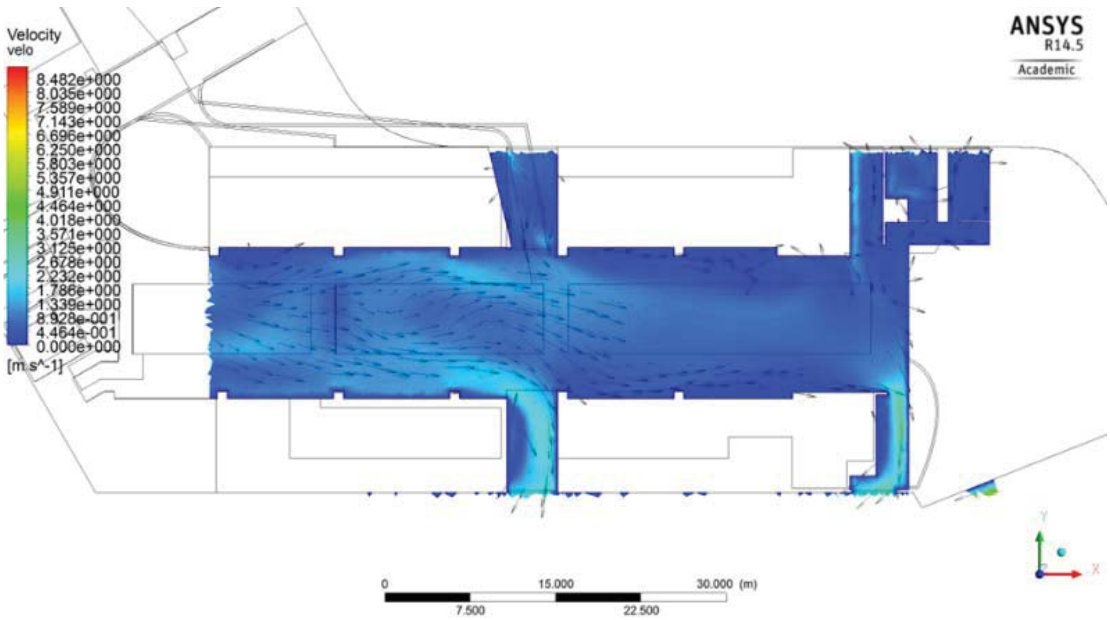

Fig. 7 Fourth level flow field results (7 m/s)

TABLE IV
COMPARISON OF 7 M/S STEADY SIMULATION

Location	Results mean velocity (m/s)	Acceptable mean velocity (m/s)	Transition Range (m/s)
Level 1	2.204	0.7 to 1.7	1.7 to 2.9
Level 4	0.7398		

VII. TRANSIENT SIMULATION: 7 M/S

Similar to the previous results, mean velocity on the fourth level, shown in Table V, remains significantly lower compared to the first level. Due to the higher wind velocity of 7 m/s, the fourth level is mostly within the acceptable range. However, given the presence of a large opening on the first level exposed to the incoming wind, the first level experiences strong wind-induced discomfort.

TABLE V
SIMULATION MEAN VELOCITY AT VARIOUS TIME (2 M/S)

Time (s)	Mean Velocity (m/s)	
	Level 1	Level 4
0.0	1.820	1.849
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VIII. DISCUSSION

A. Steady and Transient Comparison: 2m/s

Based on the steady results, it was found that the airflow on both levels was of insufficient velocity for comfort. However, based on the transient results in the first 5 seconds of flow development, the first level pedestrian wind is within an acceptable range. Thus, providing thermal comfort to pedestrians for a significant amount of time. Meanwhile, for the fourth level velocity, the mean velocity starts off in the acceptable range and falls into the insufficient wind velocity range within 3s of the transient study. The duration of comfort brought to occupants is significantly shorter compared to the first level where the comfort lasted beyond 5 s. Hence, for the 2m/s wind, the first level is sufficiently ventilated while the fourth level is insufficiently ventilated.

B. Steady and Transient Comparison: 7 m/s

The transient study showed that the peak wind speed is significantly strong. In the development of the flow, the pedestrians would be experiencing a severe spell of discomfort due to the high wind speeds. On the fourth level, wind speeds start from transition range and rapidly decrease into the acceptable range. Steady results have shown that the first level would eventually be reduced to transition range velocities. However, duration of excess velocity would cause this wind condition undesirable even if it would be able to provide sufficient wind speed to ventilate the fourth level. Although the 7m/s wind is undesirable, it represents a low possibility of occurrence. Hence, building occupants should be aware of such a possibility but no remedy action will be required to negate the effect of this wind condition.

C. 2 m/s and 7 m/s Comparison

2 m/s and 7 m/s comparison has shown that an increase of inlet wind speed will subsequently cause wind speed increase within the building. Despite the velocity difference between the wind speeds, from the flow field results (Figs. 4-7), the flow pattern remains unchanged, and this is compliant with the theory that speed has a minor role in the flow pattern [11].

Across both wind conditions, the fourth level is significantly poorer performing for wind speeds. Seen in the 7 m/s wind, the fourth level was only sufficiently ventilated when the incoming airflow is at 4 Beaufort and this wind condition has an occurrence possibility of 4% annually while causing excessive wind speeds at the first level. Two reasons have been identified that could have led to the fourth level's consistently poor performance.

- Simulation Model Error

From the simulation model validation previously, the simulation model has underestimated the velocity of along-wind flow between buildings and flow directly behind buildings. The fourth level does not immediately fit into either area, however, the fourth level area is located immediately behind an obstruction to the incoming flow. Hence, in comparison to the validation urban model, the fourth level area is an area directly behind buildings. The simulation model validated for pedestrian level flows on ground levels. The fourth level area is located at 15 m above the base of the computational domain and can be significantly affected by horizontal and vertical flow movement. In addition, when simulation model was applied to the SIT@SP domain, the inlet condition was not consistent with the proposed guidelines by AIJ [9]. Velocity profile was not modelled using the power law and the subsequent modelling of turbulent kinetic energy and dissipation rate was not used. The velocity profile was modelled by allowing the constant velocity to develop across an empty computational domain and using the outlet values as the inlet conditions. This method is also flawed as the empty computational domain failed to account for the surface roughness and thus, the boundary layer development could have been significantly different.

- Poor Building Design

Assuming the error above has no significant impact on the results. Another cause of the poor ventilation performance on the fourth floor is due to the absence of an inlet directly exposed to the incoming East wind, unlike the first level. The openings on the building façade on the fourth level are significantly smaller and located differently, much of the flow movement to the fourth level originates from the first level, moving upwards through the open main atrium shown in Fig. 8. Looking beyond the area of interest, an open side atrium, shown in Fig. 9, is exposed to the incoming flow, however, the airflow immediately enters and moves downstream out of the building. The bulk of the flow does not circulate towards the main atrium and thus, did not have a significant impact on the mean velocity in the area of interest.

Improvements to the fourth level performance would require geometrical modifications. Architectural features such as wind catchers can be added to increase the airflow entering the fourth level and thus, boosting the mean velocity in that area.

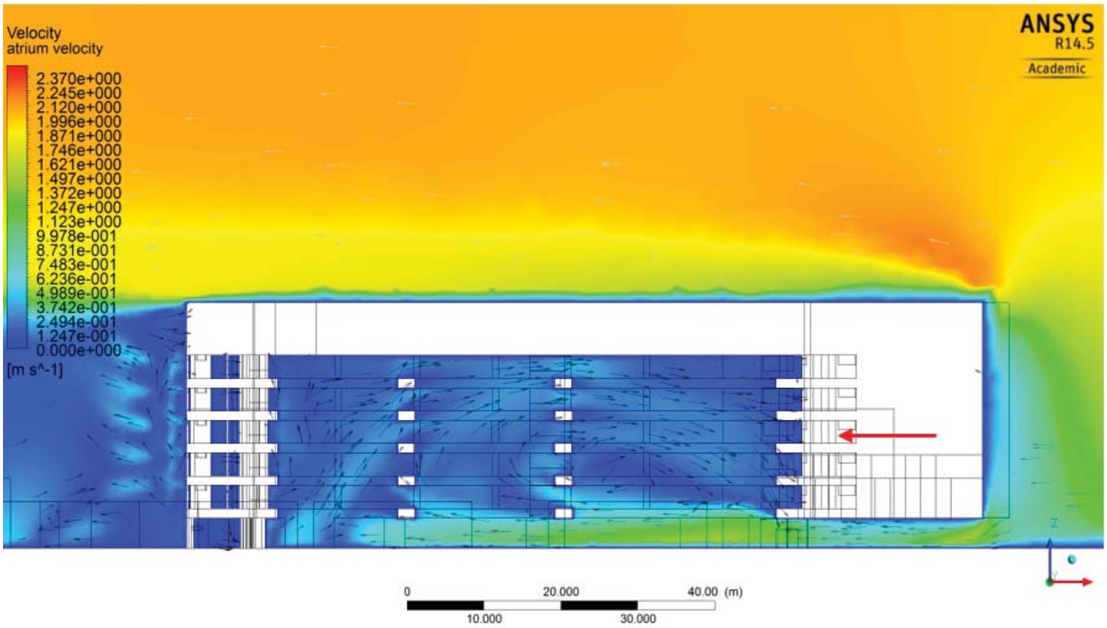

Fig. 8 Flow field of main atrium (2 m/s), arrow indicate fourth level

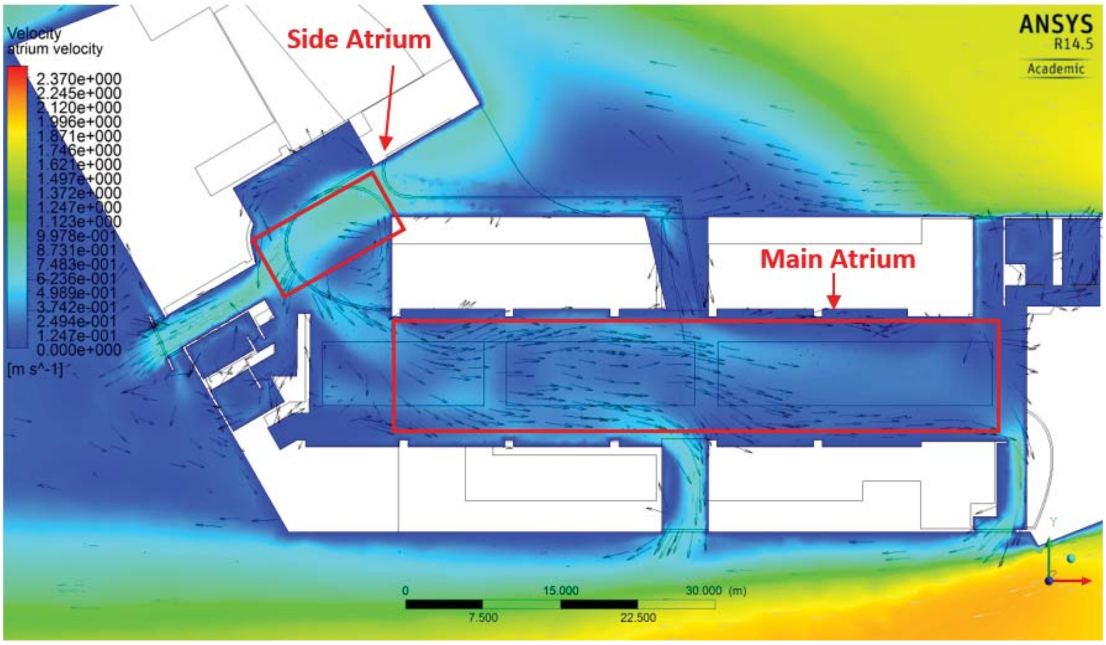

Fig. 9 Flow field for fourth level (2 m/s)

VIII. Conclusion

The objective of this analysis was to investigate pedestrian level natural ventilation at the first and fourth level of SIT@SP building using an assessment metric based on daily mean temperature and mean velocity.

Two Eastern wind conditions were studied using both steady and transient simulations. Steady simulation of 2 m/s wind showed low wind speed on both first and fourth levels, with the poorer performing fourth level wind speed at 70% lower compared to the minimum acceptable wind speed of 0.7 m/s. The transient simulation showed that first level wind speed was within the acceptable range while the fourth level wind speed rapidly fell below acceptable speed in the duration of the 5 s time period used. Thus, the first level is considered acceptably ventilated for the daily mean temperature experienced in Singapore.

A second wind speed of 7m/s was similarly investigated, steady results showed first and fourth level wind speeds to be in transition and acceptable range respectively. Transient results showed that the first level wind speed lies in the wind-induced discomfort range while the fourth level wind speed remained in the acceptable range during the 5 s time period. Thus, the 7 m/s wind was deemed undesirable due to the discomfort brought to the pedestrians.

Both wind conditions had results of a similar trend of flow patterns and the fourth level ventilation was consistently lower compared to the first level during both steady and transient simulation. This is mainly because the fourth level is located behind an obstruction to the airflow. This results in an inadequate airflow movement in that vicinity.

The general building design also suggests that there is an upper limit to the wind speeds at the fourth level. The fourth level has no inlets directed towards the incoming wind. The air movement is driven upwards from the first level through the main atrium and bulk of the air flow from the side atrium does not circulate towards the main atrium. Improvements would then involve geometrical modifications such as wind catchers to boost the airflow velocity.

IX. Future Work

Further work on this study will include: 1) modifying the urban model, 2) improvements to the simulation model, 3) use of other assessment metrics and 4) inclusion of more areas of interest in the building.

The current model uses a flat terrain for simulation. The inclusion of elevation changes may have an effect on the airflow properties as it approaches the building and thus, affecting the natural ventilation within the building. The building geometry can be modified to determine if any architectural features such as wind catchers can be added to improve the natural ventilation on the fourth level.

The simulation model can be validated for vertical accuracy. Other wind directions can be simulated to determine if the building orientation and position are optimised. It would also be possible to identify if the ventilation is significantly different when the wind direction changes at different times of the year.

Using mean velocity to assess pedestrian thermal comfort is just one of the many metrics available to quantify natural ventilation. Other metrics such as ASHRAE Standard 55 can be employed to evaluate the quality of natural ventilation within SIT@SP.

Finally, this study was focused on the ventilation of results of the main atrium area of two levels only. Similar investigations can be carried out for the remainder of the building so as to achieve a more complete and comprehensive investigation of the building.

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