The impact of façade designs: orientations, window to wall ratios and shading devices on indoor environment for naturally ventilated residential buildings in Singapore

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ABSTRACT: The impacts of building envelope designs are significant on indoor thermal environment, especially for naturally ventilated buildings. Parametric façade studies were investigated for various orientations, window sizes and shading devices by using building simulation (ESP-r) and CFD (FLUENT) coupling program to predict indoor thermal environment in an accurate and quick way. Two typical weeks were selected in May and October as the representatives of dry season and raining season in Singapore. Thermal comfort was chosen to be the criteria to evaluate different façade designs. The results suggest that the increase of window to wall ratio to 0.24, indoor thermal comfort could be largely improved and 600mm horizontal shading devices are needed for each orientation in order to improve thermal comfort in further.

Keywords: facade designs, natural ventilation, coupling program

1. INTRODUCTION

Singapore is situated on the 1.2° latitude with relatively high temperature ranging from 23□ to 34□ and high relative humidity averagely 84% in the whole year. The statistic data (PUB, 2003) of energy usage in Singapore show that domestic energy consumption rose up to 58 percent of total energy consumption in 1998 from 18 percent of total energy consumption in 1988 and energy consumption per person was increased from 950.8kW/h in 1991 to 1803 kW/h in 2001. However, 86% people in Singapore are living in HDB (Housing Developing Board) flats, which are designed to be naturally ventilated. The level of thermal comfort satisfaction provided by these high-rise residential buildings could directly determine the energy usage in the domestic sector. Those buildings with better designs for natural ventilation would probably provide better thermal comfort without air conditioning, which could largely decrease domestic energy consumption.

The climatic data analyses demonstrate that comfortable indoor thermal environment could be achieved by natural ventilation for residential buildings in Singapore (Wang and Wong, 2005). Therefore, natural ventilation is an important sustainable strategy in Singapore. The achievement of indoor thermal comfort in naturally ventilated buildings is determined by thermal performance of façade design to a large extent, ranking second to the local climatic characteristics. The purpose of this paper is to investigate different façade designs for naturally ventilated residential buildings in Singapore and provide some design guidelines.

2. NATURAL VENTILATION STUDY METHODS

Facade is considered to be the meso-environment between the micro-environment of humans and the external macro-environment, which plays an important part in contributing to a productive and comfortable individual life, especially in naturally ventilated buildings. Currently, the methods for natural ventilation study to evaluate facade performance could be summarized into three types: field measurements, experiments and simulations. However, field measurement can only collect on site data from very few buildings and the measured data can sometimes be affected by uncertainties, which create difficulties for data analyses. For the second method, the data obtained from wind tunnel experiment or full scale model experiment are more reliable and controllable than those collected in field measurement. However, the experiment can be very costly and time consuming and the data quality is also confined by the accuracy of instruments. Compared with the above methods, simulation could save the time and provide controllable results according to the requirements. Simulation method for natural ventilation could be divided into two types: Computational fluid dynamics method (CFD) and building simulation method (BS). CFD simulation could provide detailed air temperature, air velocity, contaminant concentration within the building or outdoor spaces. It has become a reliable tool for the evaluation of thermal environment and contaminant information. However, the application of CFD for natural ventilation prediction has been limited due to long computational time and excessive computer resource requirements. On the other hand, building simulation (BS) tools could greatly facilitate energy efficient sustainable building design by providing rapid prediction of facade thermal behaviors, indoor air flow of the building and better understanding of the consequences of various design decisions, through solving the heat and mass transfer and airflow network in the building systems. However, BS programs assume the indoor air is completely mixed and uniform; so BS results could only provide the uniform results for targeted spaces, which normally does not meet our requirements for detailed indoor environment evaluation.

Therefore, the integration of the BS and CFD simulation could provide a quick and more accurate way to assess the performance of natural ventilation in whole buildings, as well as detailed thermal environmental information in some particular spaces. Therefore, there is urgent need to provide an efficient coupling program between BS and CFD to predict natural ventilation efficiently and accurately. The work to integrate the CFD simulation with building simulation has been carried out in recent years. CFD program has been integrated into building simulation for air conditioned rooms to improve the evaluation of building energy consumption (Negrao, 1995 ;Zhai *et al*,2002). Djunaedy (2005) further extended the coupling program to external coupling between ESP-r thermal simulation with commercial software FLUENT for mechanical ventilation. Tan and Leon (2005) coupled a multi-zone airflow simulation program (Multi-Vent) with CFD (PHOENICS) by static strategy.

In this study, a newly developed coupling program (Wang and Wong, 2006a&b), particularly for natural ventilation prediction, has been used for accurate and efficient façade evaluation. The procedure of this coupling process, as shown in Figure 1, is to obtain the internal surface temperature, pressure at the openings, which will be saved at data exchange interface. By using the script program from the interface, the boundary conditions will be automatically fed into indoor CFD simulation for a series of hours. For indoor CFD simulation, by comparing pressure values, the opening with larger pressure value will be taken as pressure-inlet, the other opening with smaller value will be taken as pressure outlet condition. The inlet wind direction is consistent with wind direction in climatic data. The obtained zone dry bulb temperature from coupling program will be used to compare with dry bulb temperature with building simulation alone.

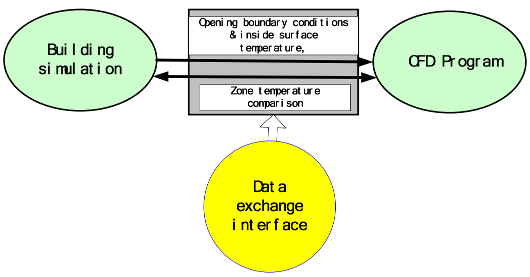

Figure 1: The coupling strategy between building simulation and CFD

3. FACADE EVALUATION CRITERIA FOR NATURAL VENTIALTION

Thermal comfort is the outstanding criteria for natural ventilation evaluation. Thermal comfort regression model (Wang and Wong, 2005) for naturally ventilated residential buildings in Singapore has been derived from 538 field survey data (Feriadi *et al* , 2003)

$$PMV = -11.7853 + 0.4232 \times Temp - 0.57889V \quad \text{(Eq.1)}$$

Where, Temp indicates the indoor air temperature and V refers to indoor air velocity measured at 1.2 m above the ground. The term PMV refers to the average (mean) response of a group exposed to a given climatic conditions rather than individual responses. As relative humidity is highly correlated with dry bulb temperature, the impacts of variation of dry bulb temperature on thermal comfort can indirectly indicate the effects of relative humidity changes on thermal comfort. In another aspect, relative humidity in hot-humid climate is always in the high level (above 60%). Therefore, the parameter relative humidity is not involved in the regression model. clo and met are normally standard for residential buildings in Singapore. clo is around 0.34-0.5 as people tends to adjust their clothes at home for better thermal comfort and met is equal to 1.0. Dry bulb temperature and air velocity are parameters for thermal comfort prediction. The acceptable thermal condition of PPD 20% can be achieved within the -1.3 and 1.1 data (Feriadi *et al*, 2003). Therefore, the upper limit of indoor discomfort is set to be PMV=1.1(20% PPD).

4. METHODOLOGY

In this study, the coupling program between building simulation (ESP-r) and indoor CFD simulation (FLUENT) are used to predict indoor thermal environment with various façade designs on the aspects of window to wall ratios, shade devices and orientations. A typical living room in HDB residential buildings block601, west coast on the sixth floor in Singapore has been chosen for this study. The layout of the HDB unit is shown in Figure 2.

A typical living room in the HDB residential buildings on the sixth floor, which holds one external wall, is the targeted subject. The living room has five openings: one window within the facade, one door connected with kitchen and the other three doors are connected with bedroom1, bedroom2 and bedroom3 respectively. The window and door connected with kitchen are assumed to be fully open and the other three doors connected with bedrooms are assumed to be close. The window within the facade in kitchen is assumed to be fully opened for 24 hours.

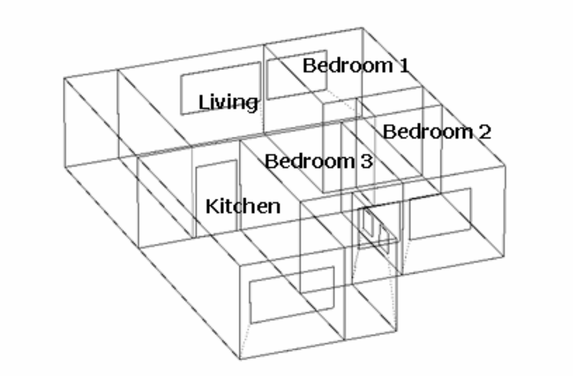

Figure 2: the layout of the four-room HDB unit

Two typical weeks in May (dry season) and October (raining season) are selected to test for thermal comfort with various façade designs. From the climatic data analysis in Singapore (Wang and Wong, 2005), the largest percentage of thermal discomfort in the typical year appears in the month of May for Singapore. The choosing of typical week in the month is outlined as follows:

a) The number of instances where the global radiation, dry bulb temperature, and wind speed in a particular hour in the week exceeds the maximum or falls below the minimum of the other weeks are added.

b) The differences in the amount of global radiation, dry bulb temperature and wind speed for each of the above instances are added separately for those above the maximum or below the maximum values.

By detailed comparison of the above parameters, any unusual traits in the day of the week for each hour could be detected. Two typical weeks (18th - 24th May and 18th -24th Oct) are selected for long term indoor thermal comfort evaluation. The percentage of hours within the thermal comfort zone in each typical week is taken as the criteria for façade design evaluation.

5. Results

In this parametric study, the combination effects of several façade design parameters in naturally ventilated buildings, including four different orientations (North, South, West and East), three various window to wall ratios (0.12, 0.24 and 0.3) and three horizontal shading dimensions (0, 600mm, 900mm), are taking into considerations. Concrete hollow block wall, which is widely used in building construction in Singapore, is taken as both external and internal wall materials in the building. Thermal transmittance of the 100mm concrete hollow block wall is 1.89 W/K m^2. The heat sources including equipments and occupants are negligible in the unit. In total, twenty-six various façade design scenarios were investigated in this paper and fifty-two cases were simulated for indoor thermal comfort evaluation, including the two typical weeks both in dry and raining seasons.

5.1 Demonstration of simulation results with coupling program

With the coupling program, indoor thermal environment could be predicted in details. We chose an hour case and simulated results as coupling program result demonstration. It is 9 AM on 18th May with the ambient temperature 30.7 ℃ and wind direction 77º(from north to east) at the wind speed of 1.4m/s. The demonstrated facade design case is east facing room with window to wall ratio 0.24 and no shading device. Figure 2-6 illustrate the detail indoor temperature, velocity magnitude, velocity vector and PMV index of the living room at 1.2m above the floor. From the PMV index in Figure 6, it can be seen that the indoor thermal comfort are non-uniform and the area with higher air velocity could provide better indoor thermal comfort than the stagnant spaces.

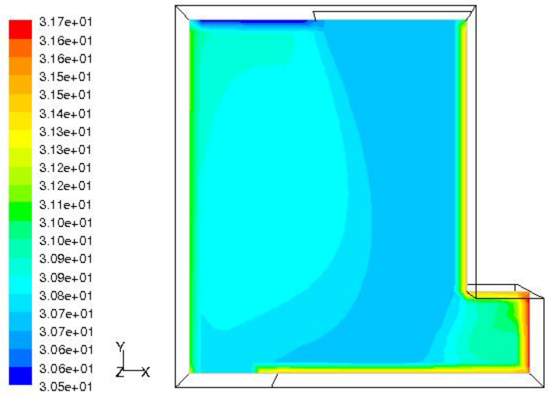

Figure 3 : Contour of indoor temperature (℃)

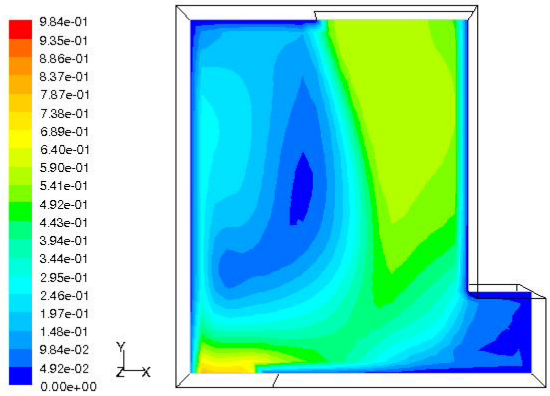

Figure 4: contour of indoor velocity magnitude (m/s)

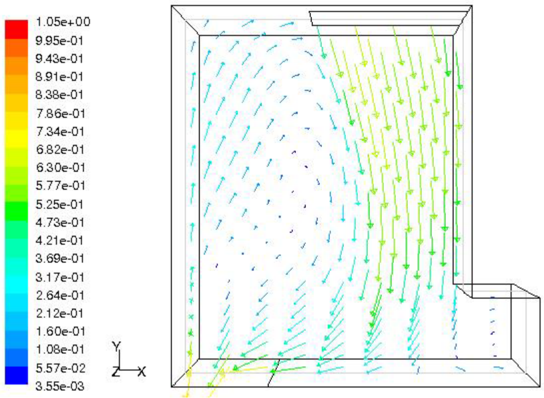

Figure 5: velocity vectors coloured by velocity magnitude (m/s)

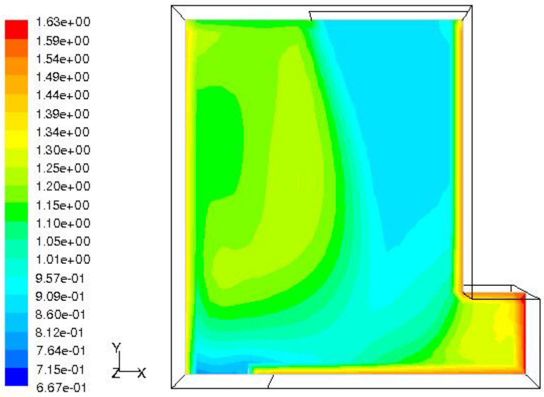

Figure 6: Contour of PMV (indoor thermal comfort index)

5.2 The results of thermal comfort percentage for various facade designs

A series of coupled simulations are carried out for twenty-six facade design options. Coupled simulations for each particular facade design are performed for two typical weeks(18th -24th May and 18th -24th Oct), and the simulation results at 1.2m level above the floor for each case are analyzed based on thermal comfort index (Eq.1) and represented by thermal comfort percentage in both typical weeks.

The simulation results for thermal comfort percentage in the typical weeks (168 hrs/week) are shown in Table 1-4 for four different orientations. It can be seen that south facing and north facing units would have much better indoor thermal environment than east facing and west facing units in Singapore.

In Table 1, it is observed that thermal comfort condition in raining season is much better that in the dry season. It could be attributed to two reasons: the ambient temperatures in the raining season are normally lower than those in the dry season; and solar heat gains in the raining season are less since solar is in the south hemisphere in the winter time. As can be seen from the results in May, indoor thermal comfort environment could be largely improved by 13% with the increase of window to wall size from 0.12 to 0.24; but there are no obvious improvement in thermal conditions when shading device are not added. This could probably indicate that the increased indoor air velocity with the increase of window to wall ratios could not compensate, or could just compensate, the indoor temperature increases with the increase of heat gains. The increase of window to wall ratios would increase indoor air velocity on the one hand, but would increase the indoor air temperature on the other hand since more heat gains from solar radiation and ambient could be induced from the larger openings. Therefore, as we can see from the results, with the 600mm horizontal shading device above the window, indoor thermal comfort environment could be further improved. For the thermal conditions in October, the shading devices do not have much effect on thermal comfort. Thermal comfort percentage in South orientation is shown in Table 2. Thermal comfort conditions for south facing room are generally good in both dry and raining seasons. There is an obvious improvement in thermal comfort when the window to wall ratios has been increased to 0.24 and 600mm horizontal shading device are needed for better thermal comfort when solar is in the south hemisphere.

Table 3 and Table 4 illustrate the results of thermal comfort percentage for east and west orientations. Compared with the other two orientations, thermal comfort percentages in the two typical weeks for east and west facing room are much lower. Same as the other orientations, the increase of window to wall ratios to 0.24 could largely improve indoor thermal comfort by increasing indoor air velocity. Horizontal shading device are needed for both orientations to further improve the indoor thermal comfort. However, with the increase of the length of shading device to 900mm, thermal comfort percentage in the typical week in May for west orientation is still too low to meet thermal comfort requirements in most of the time. Under this condition, mechanical fans may probably be used to improve indoor thermal comfort. East or west facing rooms should be avoided for residential buildings for the purpose of thermal comfort and energy consumption in Singapore. By any means, the improvement of façade designs in naturally ventilated buildings could largely alleviate the burden of energy crisis and provide us a natural and comfortable indoor environment.

Table 1: Thermal comfort percentage in two typical weeks in North orientation

WWR	SHADING	Thermal comfort percentage	
		Typical week in May	Typical week in Oct.
0.121	0	52.98	80.23
0.121	600	55.95	80.95
0.24	0	66.07	88.09
0.24	600	70.8	88.09
0.3	0	66.67	88.09
0.3	600	72.02	88.09

Table 2: Thermal comfort percentage in two typical weeks in South orientation

WWR	SHADING	Thermal comfort percentage	
		Typical week in May	Typical week in Oct.
0.121	0	72.62	81.54
0.121	600	72.62	83.33
0.24	0	78.57	83.9
0.24	600	78.57	86.9
0.3	0	77.97	84.52
0.3	600	77.97	86.9

Table 3: Thermal comfort percentage in two typical weeks in East orientation

WWR	SHADING	Thermal comfort percentage	
		Typical week in May	Typical week in Oct.
0.121	0	52.97	54.16
0.121	600	55.35	56.28
0.24	0	64.88	69.04
0.24	600	66.07	70.24
0.3	0	64.88	69.04
0.3	600	66.07	69.6
0.3	900	66.07	70.24

Table 4: Thermal comfort percentage in two typical weeks in West orientation

WWR	SHADING	Thermal comfort percentage	
		Typical week in May	Typical week in Oct.
0.121	0	46.42	57.14
0.121	600	46.42	58.93
0.24	0	53.57	62.27
0.24	600	54.17	64.28
0.3	0	53.57	63.09
0.3	600	54.17	63.09
0.3	900	55.35	63.09

6. DISCUSSION

Façade designs for natural ventilation is a challenging task, which is related to indoor thermal comfort and domestic energy consumption. There are several important façade design parameters. However, it would probably be biased to simply take one parameter into account and neglect others. Thermal comfort could be used as the criteria to evaluate the combination effect of different façade design parameters. The coupling program between BS and CFD simulation could accurately and quickly predict indoor thermal environment, which provide a more convenient tool for façade design evaluation of naturally ventilated buildings.

The façade design parameters including orientations, window to wall ratios, and the dimensions of shading device are taken into account in this parametric study. It could be concluded that south and north facing units would have much better indoor thermal environment than east facing and west facing units in Singapore. The increase of window to wall ratio to 0.24 could improve indoor thermal conditions to a large extent. 600mm horizontal shading device are needed for the four orientations for further improvement in indoor thermal comfort. In the future studies, other shade devices like vertical fins or the combination of both vertical fins and horizontal shading devices could be investigated on west and east facing facade in order to provide better indoor thermal comfort.

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