Impact of façade design on building thermal performance in tropical climate

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Abstract— *This study investigates the impact of building facade design on air temperature and surface heat gain in tropical climate. Field experiment was firstly carried out to measure the impact of window-to-wall ratio, orientation and shading device on indoor air temperature and building surface temperature. Computer simulation using EnergyPlus was then carried out to simulate the thermal and energy performance of different building facade. The model was validated against the experimental data, with the Cumulative Variation of Root Mean Square Error (CVRMBE) to be less than 5% in all the air and surface temperature predictions. The impact of facade design on the indoor cooling load was predicted. Recommendations were provided to design the building façade with better performance in tropical climate.*

Keywords: thermal performace, heat gain, residential envelope, orientation, window-to-wall ratio, shading device.

I. INTRODUCTION

The building envelope that separates indoor space from outdoor environment plays a significant role in the passive control of indoor environment. Currently, more than 80% of the country's population live in the public housing in Singapore. Some passive design features have been adopted, such as north-south oriented windows, extended canopies to provide shading, casement windows to promote natural ventilation, etc. However, the buildings developed by private developers (condominiums) tend to have less emphasis on promoting natural ventilation and other passive design strategies. Most condominiums use full-height glass façade to offer a better view and create luxurious appearance to attract buyers. In recent years, this design feature has been gradually adopted by designers of public housing as well, which is a condominium-like design. Therefore, it is timely for this study to understand how this new trend of façade design affects the energy consumption in residential buildings.

Extensive research work has been carried out on the passive design of building envelope for indoor thermal comfort and cooling energy savings in Singapore. Field experiments were done to examine the potential benefits of using passive roofs, such as rooftop garden [1], solar-reflective cool roof, secondary roof [2]. The impacts of orientation, floor level and shading device on the thermal performance of building facade and indoor thermal comfort were also studied [3]. In addition, simulation studies were conducted to analyze the impact of other parameters on the thermal performance of building facade, such as thermal insulation, induced natural ventilation flow, window-to-wall ratio (WWR) and shading devices [4].

The objectives of this study are to understand the impacts of façade design parameters on the thermal performance and indoor cooling load of point-type block in the tropical climate of Singapore. Passive design recommendations are provided to improve the indoor thermal comfort. Both field measurement and parametric study are employed to fulfill the objectives.

II. FIELD MEASUREMENT

We conducted a 1-week field measurement in three units (see Fig. 1) of KV2 in Singapore. KV2 was an impressive development completed in 2012 and was designed to be eco-friendly.

Fig. 1 Map of measured units in KV 2

Three units in 3 different blocks were selected for field measurement, and they were named as Unit G, H and I according to the block number. As shown in Fig. 2, the field measurement lasted for 1 week, and windows were kept open during daytime and closed at night. In field measurement, we measured the air temperature, wall surface temperature and indoor wind speed in the three selected units. All the parameters are measured at 1-minute interval. The impacts of orientation, WWR and internal shading blind on the indoor air temperature on a sunny day (Nov 25, 2016) were analyzed.

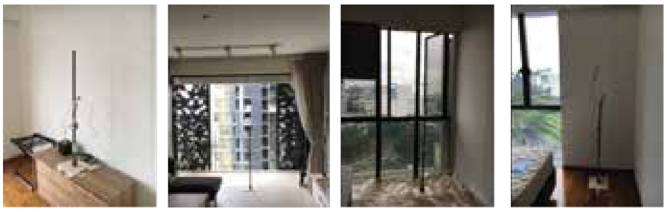


Fig. 2. Field measurement (a) near wall in living room, (b) near balcony, (c) near bedroom window and (d) bedroom wall.

A. Impact of orientation

Air temperatures near the living room walls of Units G and H with different orientations were compared. As shown in Fig. 3, the northwest-facing wall in living room of Unit H was hotter than the southeast-facing wall in living room of Unit G during the whole day. The daily maximum air temperatures near walls appeared at 17:00, and were 32.8°C in Unit H and 30.0°C in Unit G respectively. The daily average air temperature in Unit H was 1.9°C higher than that in Unit G.

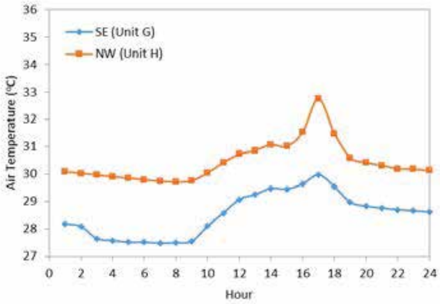


Fig. 3. Air temperature near walls with different orientations.

The internal surface temperatures of these two walls were also compared. As shown in Fig. 4, the surface temperature of northwest-facing wall in Unit H was continuously higher than the southeast-facing wall in Unit G. The maximum temperature difference of 1.6°C appeared at 17:00 and minimum temperature difference of 1.2°C appeared at 14:00. The daily maximum temperatures of internal wall surfaces were 30.3°C in Unit H at 17:00 and 28.8°C in Unit G 18:00 respectively. The daily average surface temperature of southeast-facing wall in Unit G was 1.3°C lower that of northwest-facing wall in Unit H. The daily minimum temperatures of two internal appeared around 09:00.

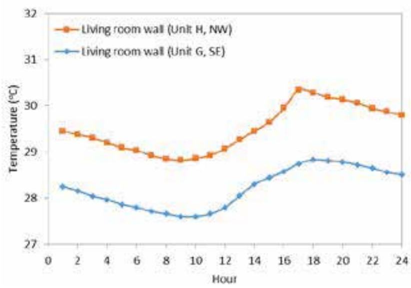


Fig. 4. Internal surface temperatures of walls with different orientations.

B. Impact of window-to-wall ratio

The northwest-facing façade of master bedroom in Unit I is made of big window and narrow wall. Air temperatures near the window (WWR=0.8) and near the wall (WWR=0) were compared. As shown in Fig. 5, air temperature near the window was higher than that near the wall from 09:00 to 18:00 with an average difference of 0.7°C. The daily maximum air temperatures near the two facades appeared at 17:00, which were 32.4°C near wall and 31.4°C near window respectively. At night, the situation was reversed. The air temperature near window became slightly lower than that near wall.

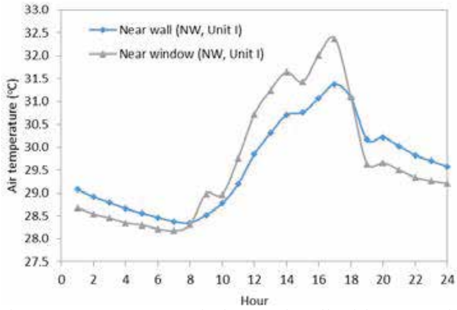


Fig. 5. Air temperatures near window and wall with same orientation.

C. Impact of internal blind

The air temperatures near the windows of two bedrooms in Unit I were compared, where internal blind was used in one bedroom and not used in another. The two bedroom windows have similar size and same orientation. Both windows were kept closed during the measurement period.

From Fig. 6, it is observed that the daily minimum and maximum air temperatures appeared at 07:00 and 17:00 respectively in both bedrooms. The window covered with blind was cooler than that without blind from 10:00 to 18:00, with the average temperature difference of 1.1°C. At 17:00, the blind helped to reduce air temperature by 1.7°C from 33.3°C to 31.6°C. At night, the situation was reversed. The bedroom with blind was on average 0.7°C warmer than the one without blind from 20:00 and 07:00.

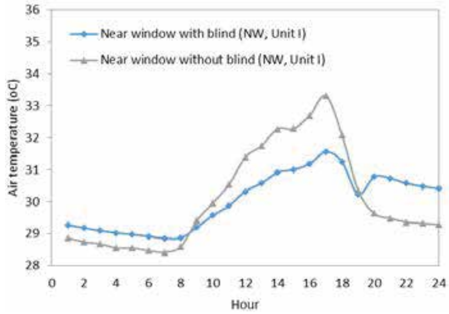


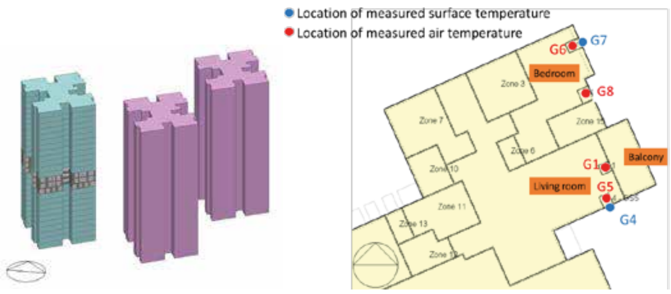
Fig. 6. Air temperature in common bedrooms with and without blind.

III. Computer Simulation

Parametric study was conducted to predict the impacts of WWR, orientation and shading device on the surface heat gain of building façade under Singapore climate. Computer simulation was performed using EnergyPlus software, and the computer model was validated by the experimental results.

A. Validation of EnergyPlus model

The measured data in Unit G of KV 2 were used to validate the energy simulation model. As shown in Fig. 7 (a), the units located above and under the measured unit were also modeled to avoid the influence from ceiling and floor. All the modeled units were naturally ventilated with the air-conditioning system off. In addition, the drawings and material information of KV2 were used to build up the geometric and physical model. Weather data collected at a nearby weather station were used as background weather input, including solar radiation, precipitation, wind speed, air temperature and etc.



(a) (b)

Fig. 7. (a) Simulated blocks and floors, (b) Simulated zones and temperatures for model validation

The wall of simulated block was mainly made of 20-cm reinforced concrete with a U-value of 3.304 W/m^2 K, and the glass was 8-mm grey class with a U-value of 5.92 W/m^2 K. The shading device on each façade was also modeled in details.

The simulated air and surface temperatures were compared with those measured ones for different locations in Unit G, as shown in Fig. 7 (b). Two indicative parameters were selected to evaluate the accuracy of simulation results [5]. One is the mean bias error (MBE), and another one is the cumulative variation of root mean square error (CVRMSE). These two parameters are calculated based on the equations below [6]:

$$MBE = \frac{\sum_{i=1}^{24}(Mi - Si)}{\sum_{1=1}^{24} Mi} \quad (1)$$

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{24}\left((Mi - Si)^2/24\right)}}{\sum_{1=1}^{24} Mi/24} \quad (2)$$

where *Mi* and *Si* are the hourly measurement data and simulation data respectively. Fig. 8 (a)-(f) show the comparisons between the hourly measured and simulated temperatures. The *MBE*s in all the predictions were between 2% and 5%, and all the *CVRMBE*s were less than 5%. According ASHRAE criteria [6], the model is validated if *MBE* is less than 10% and *CVRMSE* is below 30%. Satisfactory agreements were obtained between the measured and simulated results.

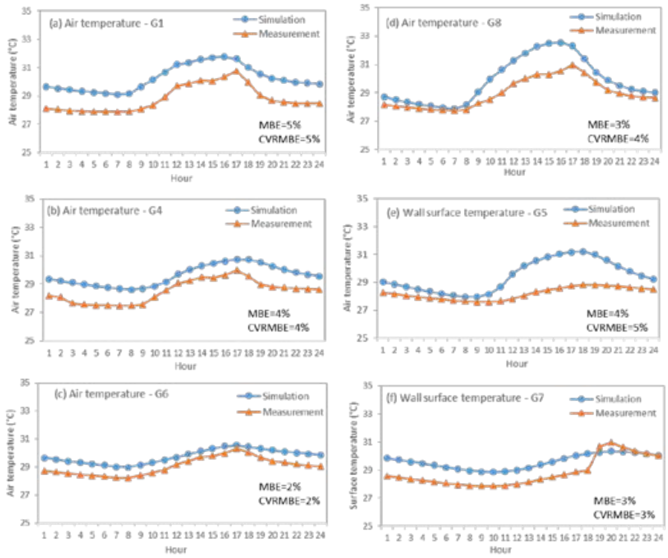


Fig. 8. Comparison between simulated and measured temperatures.

B Parametric study

The geometry model of KV2 and corresponding material properties were used as a base model in parametric study. The orientation, WWR and shading device of the base model were varied to analyze their impact on the thermal performance of building façade.

1) Impact of orientation

The monthly surface heat gain of walls with different orientations were analyzed. As shown in Fig. 9, the north-facing wall shows the lowest monthly surface heat gain from Jan to Mar and from Oct to Dec, while the south-facing wall has the lowest heat gain from Apr to Sep. Moreover, the south-facing wall has the highest heat gain in Jan and Dec, and the north facing-wall has the highest heat in Jul and Aug. Moreover, the annual heat gain of walls decrease gradually with the increase in WWR for all the orientations. When WWR is 0 with no window, the east-facing wall has the highest annual heat gain of 3583 kWh, followed by west, southeast, northeast, northwest, southwest, north and south orientations.

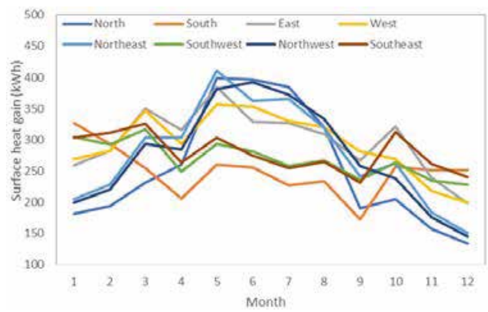


Fig. 9. Monthly surface heat gain of walls with different orientations.

The monthly surface heat gain of windows with different orientations were analyzed as well, as shown in Fig. 10. When WWR is 1, the north-facing window has the lowest monthly gain from Jan to Apr and from Oct to Dec, and the south-facing wall has the lowest heat gain from May to Sep. Moreover, the south-facing window has the highest heat gain in Jan and Dec, and the north-facing window has the highest heat gain in Jun and Jul. When the WWR is 1, the east-facing window has the highest annual heat gain of 17441 kWh, followed by west, southeast, northeast, northwest, southwest, north and south orientations.

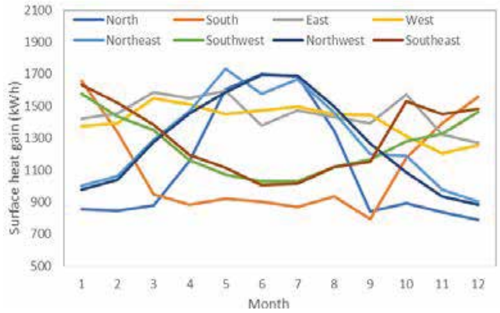


Fig. 10. Monthly surface heat gain of windows in different orientations.

2) Impact of window-to-wall ratio

The impact of WWR on the heat gain of facade with different orientations was studied. As shown in Fig. 11, the annual heat gain of the façade increases almost linearly with the increase in WWR for all the orientations. When the WWR increases from 0 to 1, the east-facing surface with the highest annual heat gain increases from 3583 kWh to 17441 kWh, and the south-facing surface with the lowest annual heat gain increases from 2994 kWh to 13366 kWh.

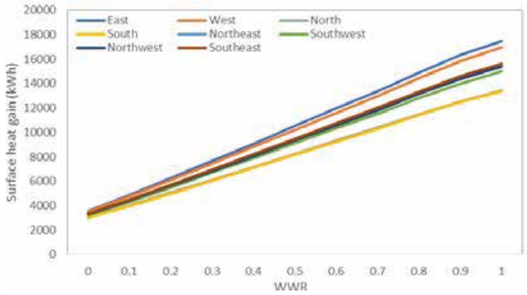


Fig. 11. Annual surface heat gain for variable WWRs of different orientations

The impact of WWR on the hourly surface heat gain of façade with different orientation was simulated as well, for the east, west, north and south orientations respectively. Weather data on a representative day of Apr 30 was used as model input.

The hourly heat gains of east-facing façades on 30th Apr with the WWRs varying from 0 to 1 are shown in Fig. 11 (a). It is observed that the surface heat gain decreases with the increase in WWR during the daytime from 08:00 to 17:00. The surface heat gains of east-facing façade surfaces with WWRs ranging from 0.2 to 1 reach their maximum at 11:00, which are 1.95 kW and 8.63 kW for the façades with WWR of 0.2 and 1 respectively. However, the situation is reversed at night, as windows help to dissipate heat. The façade surface with larger WWR has smaller heat gain before 06:00 and after 20:00.

The hourly heat gains of west-facing façades on 30th Apr with the WWRs varying from 0 to 1 are shown in Fig. 11 (b). It is observed that the surface heat gain decreases with the increase in WWR from 09:00 to 18:00, and the situation is reversed at night. The heat gains of façade surfaces reach their maximum at 16:00 for surfaces with WWRs ranging from 0.2 to 1. The maximum heat gain of west-facing façade with WWR of 1 is 8.28 kW at 16:00.

The hourly heat gains of north-facing façades on 30th Apr with WWR varying from 0 to 1 are shown in Fig. 11 (c). It is observed that the surface heat gain decreases with the increase in WWR from 08:00 to 18:00, and the situation is reversed at night. The heat gains of façades reach their maximum during 14:00 and 16:00 for surfaces with WWRs ranging from 0.2 to 1. The maximum heat gain of north-facing façade with WWR of 1 is 6.97 kW at 14:00.

The hourly heat gains of south-facing façades on 30th Apr with WWRs varying from 0 to 1 are shown in Fig. 9 (d). It is observed that the surface heat gain decreases with the increase in WWR from 09:00 to 18:00, and the situation is reversed at night. The heat gains of façades reach their maximum at 15:00 for surfaces with WWRs ranging from 0.2 to 1. The maximum heat gain of south-facing façade with WWR of 1 is 5.18 kW at 15:00.

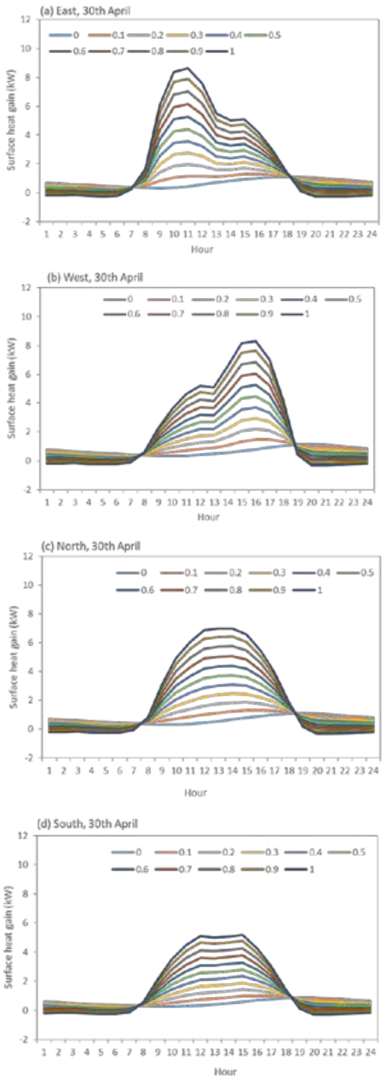


Fig. 11. Hourly heat gain of façade of different WWRs in (a) east, (b) west, (c) north and (d) south orientations.

3) Impact of shading

The impact of shading device on the surface heat gain of façade is investigated. Two types of shading devices were explored, namely horizontal overhang and vertical side fin. The two windows on the studied facades have the same dimension of 2.4 m in width and 1.5 m in height. All other walls except for the studied facade in the baseline model were designed with no windows to avoid the influence of solar access from other windows.

a) Horizontal overhang

The impact of depth of horizontal overhang on the studied façade was studied. As shown in Fig. 10, the windows with east and west orientations have the highest heat gains for all the shade depths, followed by the northeast, southeast, northwest, southwest, north and south orientations. A sharp drop in heat gain is observed when the depth of overhang increases from 0 to 0.7 m. When depth of horizontal overhang varies from 0.7 m to 1.5 m, there is no significant decrease of heat gain. The annual heat gains of windows reduce with the increase in shade depth. For all the orientations, the annual heat gains reduce by 21%-23% when the shade depth increases from 0 to 0.5 m. The reductions increase further to 30%-34% and 34%-40% when the shade depth increases to 1 m and 1.5 m.

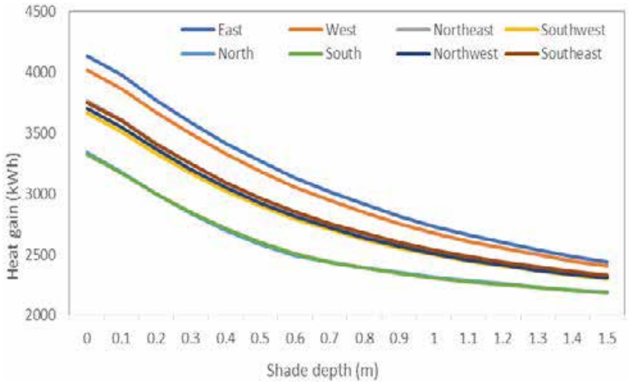


Fig. 10. Annual window heat gain with different depth of horizontal shading device

b) Vertical side fins

The impact of vertical shading device such as the side fins on the heat gain of windows was also studied. As shown in Fig. 11, the annual heat gain of windows with different orientations reduce evidently with the depth of vertical fins increases from 0 to 1.5 m. Windows with east and west orientations show the highest heat gains for all the fin depths, followed by the northeast, southeast, northwest, southwest, north and south orientations. For all the orientations, the annual heat gains reduce by 7%-9% when the shade depth increases from 0 to 0.5 m. The reductions increase further to 11%-14% and 15%-18% when the shade depth increases to 1 m and 1.5 m. The reductions are less significant than those achieved by horizontal overhangs.

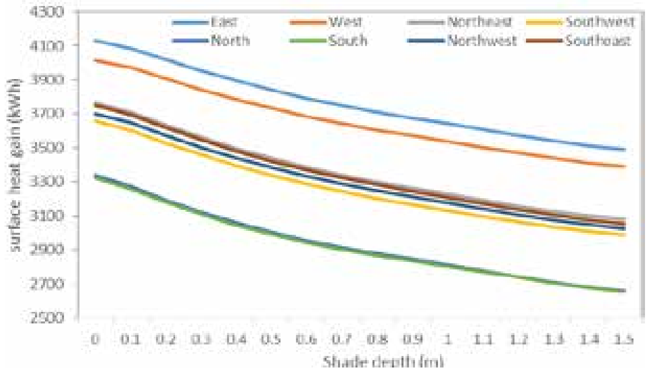


Fig. 11. Annual window heat gain for different orientations with variable shading depth

IV. Conclusions

In this study, the thermal performance of building façade in tropical climate of Singapore was evaluated. From field measurement, it is found that the maximum air temperature near northwest-facing wall is 2.8°C higher than that near southeast-facing wall. The daily average surface temperature of northwest-facing wall was 1.3°C higher than that of southeast-facing wall. Moreover, the air temperature near wall is 1°C lower than that near window with the same northwest orientation. The internal blind could reduce the peak indoor air temperature by 1.7°C.

From energy simulation results, it is found that surfaces east and west orientations receive most annual heat gain among the eight orientations. The heat gain of façade increases evidently when the WWR increases from 0 to 1 for facades in all the eight orientations. Moreover, shading devices help to reduce the solar heat gain from windows significantly. Compared to horizontal overhang, vertical side fins contribute less to solar heat gain reduction in tropics. The shading devices are most effective on the east-facing and west-facing facades. The results obtained in this study could provide design guidelines for the architects and building engineers.

V. Acknowledgement

This project is funded by Building and Construction Authority (BCA) - Green Buildings Innovation Cluster (GBIC), with funding from the National Research Foundation (NRF) Singapore (WBS: R-296-000-169-490).

Reference

[1] W. Nyuk Hien, T. Puay Yok, and C. Yu, Study of thermal performance of extensive rooftop greenery systems in the tropical climate, Building and Environment, 42.1 (2007) 25-54.
[2] S. Tong et al., Thermal performance of concrete-based roofs in tropical climate, Energy and Buildings, 76 (2014) 392-401.
[3] N. H. Wong and S. Li, A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore, Building and Environment, 42.3 (2007) 1395-1405.
[4] L. Wang, H. Wong Nyuk, and S. Li, Facade design optimization for naturally ventilated residential buildings in Singapore, Energy and Buildings, 39.8 (2007) 954-961.
[5] Raftery, Paul, Marcus Keane, and Andrea Costa. Calibrating whole building energy models: Detailed case study using hourly measured data. Energy and Buildings, 43.12 (2011) 3666-3679.
[6] ASHRAE Guideline. Guideline 14-2002. Measurement of Energy and Demand Savings, American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE), Atlanta, GA (2002).