

Urban Geometry, Indoor Thermal Comfort and Cooling Load: An Empirical Study on High-Density Tropical Housing

Kam Shing Leung and Koen Steemers

Department of Architecture, University of Cambridge, UK

Abstract

This paper contributes to climate-responsive design in contemporary tropical cities by identifying the urban geometric features that influence the environmental performance of high-density housing. The indoor thermal conditions and electricity consumption of 275 households in Singaporean public housing were surveyed. Their geometric and radiant properties were concurrently studied with graphical analyses and computer simulations.

Simulated solar irradiation on façade, flat orientation and urban-form prototype are found to be significantly correlated with perceived indoor thermal comfort while the vertical position and the average sky view factor of flats are shown to be insignificant. Direct but not diffuse solar irradiation on the windows of major rooms is shown to be significantly correlated with perceived sunlight and daytime thermal comfort. Respondents in west-facing flats generally reported greater daytime and night-time thermal discomfort and these flats consumed 33% more electricity than the average. Respondents in a tall tower cluster perceived greater night-time indoor thermal comfort and air circulation, whereas those in a cluster of shorter block forming semi-open courtyards perceived indoor air circulation and greater electricity consumption.

Furthermore, based on the findings that perceived air circulation has a stronger effect than perceived sunlight on indoor thermal comfort and 70% of occupancy time was from 7pm to 7am when there is no sunlight, it is suggested that enhancing wind should be prioritised over reducing sunlight if the two objectives cannot be reconciled in the hot and humid climate.

Keywords: *high-density housing, climate-responsive design, indoor thermal comfort, cooling load, hot and humid, urban form.*

1 Research Objective

Passive cooling is a major strategy for reducing energy consumption in tropical housing since air-conditioning accounts for a significant portion of energy consumption in residential buildings (Joseph C. Lam, 1996). It is often achieved by enhancing air circulation and reducing solar heat gain in dwelling units through façade design. In high-density housing where considerable urban obstruction exists, passive cooling potential is also influenced by the geometry of adjacent buildings. Due to their size and proximity, adjacent buildings modify the amount of sunlight and wind that individual flats are subject to. The presence of multiple dwelling units in a single building also means that the environmental condition of flats in different vertical positions or orientations can vary significantly. Therefore, the urban geometry becomes an indispensable component in evaluating the indoor thermal environment in high-density housing.

Two common approaches are adopted to study the above effects. First, simulations are performed to understand the effect of urban morphological variations on wind and solar radiation. For example, Kubota et al (2008) performed wind tunnel test on the models of 22 real residential building clusters in Japan and demonstrated the negative correlation between site coverage and urban air ventilation potential. Ng et al (in Bay and Ong, 2006) applied computer simulation programs and wind tunnel test to demonstrate the favourable effects of height variations on the air exchange and daylight access of individual flats. Leung and Steemers (2009) developed a RADIANCE-based simulation technique based on Perez et al (1993) and Compagnon (2004) to identify the common urban morphological variations that affect the amount and distribution of solar irradiation on high-density housing clusters. These studies, however, only revealed the microclimatic conditions between buildings or on building facades. It is not certain whether and how these differences would influence the indoor thermal environment and the cooling load of buildings.

Second, empirical studies have been performed to understand the thermal sensation, electricity consumption and other environmental perceptions of people living in flats that are subject to different urban environment. Wong et al. (2002) studied the thermal and wind sensations of 257 residents in Singaporean public housing and suggested that thermal sensations vary between residents living in flats with different sizes and vertical positions. Lucas Souza et al. (2004) studied the electricity consumption of 20 low-rise buildings in an urban context and suggested that the orientation and the sky view factor (SVF) of their adjacent street canyons had an effect on electricity consumption. However, results from these studies were not statistically tested and the opposing effects of wind and solar radiation were not analysed.

This paper therefore aims to confirm whether and how exposure to different urban geometries affects the indoor thermal environment and cooling load of a flat. The ultimate goal is to identify the urban-form prototypes and physical

design strategies that are favourable to the indoor thermal comfort and cooling energy conservation of high-density housing in the hot and humid climate.

2 Methodology

2.1 Survey design

The survey was conducted in four building groups in two Singaporean new towns as shown in Figure 1, which offered 3041 prospective households for the survey. These building groups were selected to maximise variations in urban geometry while minimising other design variations. To determine the effect of the urban form, efforts were made to select building groups in which the façade and layout of dwelling units are similar within each group.

A mail survey was conducted in July 2009 with the questionnaire refined based on a pilot study and comments from environmental design professionals in Singapore. Control questions were built into the questionnaire to ensure the authenticity of responses. A total of 275 valid returns were received, among which 215 sets of useful information concerning electricity consumption and 263 sets concerning perceived indoor thermal conditions were obtained. Respondents represented a largely equal gender split and covered the full range of ages and income groups on aggregate and within each building group.

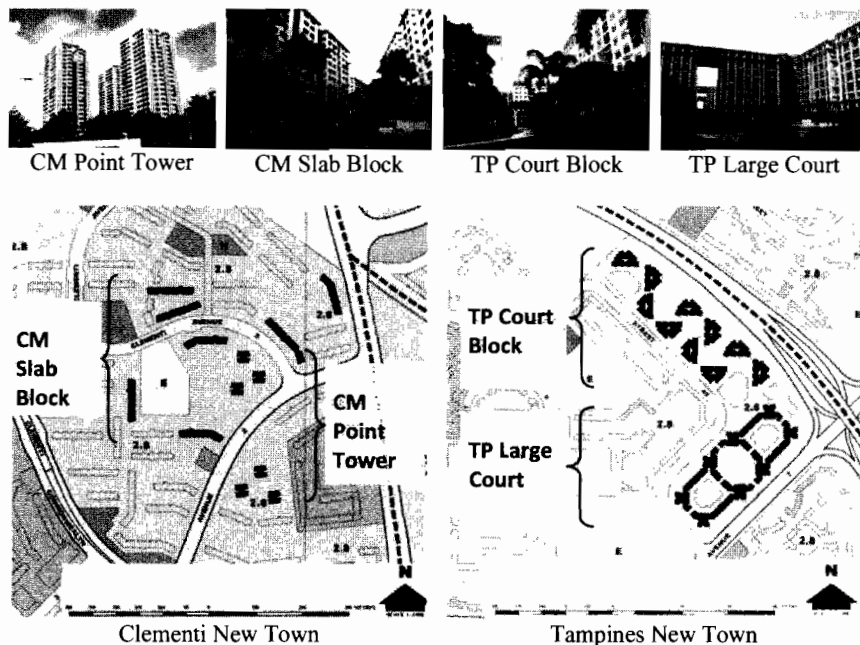


Figure 1: The four building groups selected for the survey (Source of base maps: *Master Plan 2003*, Urban Redevelopment Authority, Singapore)

Dependent variables

Daytime thermal comfort, night-time thermal comfort and average electricity consumptions are the three major dependent variables. Based on the seven-point Bedford scale (Auliciems, 1981) that has been widely used in thermal comfort study, respondents were asked to express their general perception in their flats assuming that no mechanical cooling was used. They were also requested to write down their monthly electricity consumption in kWh from January to June based on the values printed on their June utility bill. The flat type-specific national average electricity consumption was also requested. The authenticity of survey responses was validated by the agreement between this number and the values provided by the utility company.

Independent variables

Three sets of independent variables were used to correlate with the above dependent variables. The first set included the physical attributes of flats, which were based on the graphical studies of building plans and computer simulations on the solar irradiation on building facades. The second set was obtained from the survey and included occupant's perceptions on environmental factors that are related to thermal comfort. The third set included control variables that relate to neither the urban geometry nor the thermal environment but bear theoretical relationships with household electricity consumption. These variables were obtained from both the survey and the study of relevant building plans. Table 1 lists out all variables that were investigated in the study.

Table 1: Dependent, independent and control variables in the study

Dependent (from survey)	Independent set 1 (from graphical analysis and computer simulation)	Independent set 2 (from survey)
▪ Daytime thermal comfort ▪ Night-time thermal comfort ▪ Average monthly electricity consumption	▪ Orientation ▪ Vertical location ▪ Weighted-average sky view factor (SVF) of windows ▪ Solar irradiation on major windows per floor area	▪ Perceived sunlight ▪ Perceived air circulation ▪ Perceived humidity
		Control variables (from survey)
		▪ Occupancy hours ▪ Flat size ▪ Household income

2.2 Preparation for statistical analyses

Identify control variables

In order of the strength of the correlation, occupancy period (in terms of person-hours in a normal weekday), flat size and monthly household income were found to correlate significantly with the electricity consumption of flats. Regression analyses showed that these control factors account for approximately 38% of variations in electricity consumption

The average electricity consumption data were found to deviate from normal distribution. After logarithmic transformation, the electricity consumption data were shown to exhibit normal distributions for both the whole data set and the data sets of individual building groups. Further test on the transformed data also showed that all the assumptions of parametric tests were met. Therefore, parametric tests were applied to correlation analyses between electricity consumption and interval-level variables.

Perceived daytime/night-time thermal comfort, sunlight, air circulation and humidity were expressed based on preference scales. These are ordinal measurements and therefore non-parametric tests were applied to correlation analyses involving these variables.

Calculation of solar irradiation and sky view factor

Studies on the effect of solar irradiation and sky view factor were focused on CM Point Tower and TP Court Block. They were selected for their homogeneity in façade design and flat layouts, which helped reveal the sole effect of urban geometry. Since the effect of urban geometry is the research focus, design details such as window openings, façade motifs and sun-shading devices were not included in the computer model. RADIANCE, a computer programme developed by the Lawrence Berkeley Laboratory and had been widely used in lighting- and solar radiation-related studies, was used to simulate the amount of solar radiation that enters major rooms (i.e. living rooms, dining rooms and bedrooms). “Virtual pyranometers” were assigned to the mid-points of the windows of these major uses. The amount of direct and diffuse solar irradiation that reaches the window was then estimated by multiplying the solar irradiance by the corresponding window size.

The hourly simulations of solar irradiation on the 120 surveyed flats in CM Point Tower and TP Court Block for a six-month period were beyond the available computing power. An aggregate sky was therefore constructed to represent the total solar radiation from the sky during the six-month period. Such method had previously been adopted in the PRECis and SOLURBAN projects (Compagnon, 2004). The tailoring of the method for this particular study can be found in Leung and Steemers (2009). Hourly variations in direct and diffuse solar radiation during the surveyed period were obtained from the Typical Meteorological Year (TMY) Data obtained from the US Department of Energy website (U.S. Department of Energy, 2008). They were adjusted to match the actual monthly global solar radiation values that were available from the Department of Geography of the National University of Singapore (Roth, n.d.) in order to resemble the actual sky condition.

The sky view factors (SVF) of major windows in a flat were also calculated with RADIANCE simulations by assuming a uniform sky. They were given by the ratio of solar irradiation on a point with the presence of urban obstructions to that without obstructions (Compagnon, 2004).

3 Findings

Research findings are reported under four groups of correlation analyses that aim to reveal the potential effect of the following parameters on the perceived daytime/night thermal comfort and the electricity consumption of flats:

1. Solar irradiation on major windows – Section 3.1;
2. Simple geometric measurements (i.e. flat orientation, vertical position and average sky view factor) – Section 3.2;
3. Urban-form prototypes (i.e. point towers, slab blocks, large courtyards and lower blocks forming semi-courtyards) – Section 3.3; and
4. Perceived indoor environmental factors (sunlight, air circulation, humidity) – Section 3.4.

3.1 Effect of solar irradiation on thermal comfort and electricity consumption

Effect on daytime and night-time thermal comfort

In theory, greater solar irradiation on windows leads to a hotter indoor thermal environment and higher cooling load. In a high-density urban setting, however, a higher level of solar irradiation may also represent less urban obstruction and therefore a greater exposure to wind that moderates the indoor thermal environment. This study therefore attempts to ascertain whether solar irradiation on the windows provides a good indicator for the impact of urban geometry on indoor thermal comfort.

Solar radiation through windows was shown to have by far the largest effect on solar heat gain as compared to heat conduction through opaque walls or the window glass (Lam et al., 1993). Therefore, solar irradiation on a flat was defined as the amount of solar irradiation on the windows of major rooms per floor area in this study.

As tabulated in Table 2, non-parametric tests on both CM Point Tower and TP Court Block show that direct solar irradiation on windows possesses large and significant correlations with daytime thermal comfort and perceived sunlight, while diffuse solar irradiation does not exhibit such relationship. Although the total amount of diffuse solar irradiation on building façades is much higher than that of the direct component in Singapore, the direct component alone serves as a better indicator for the effect of solar heat gain. It is believed to be because direct irradiation is intensively received by individual flats during a shorter period of time while diffuse irradiation is more evenly received throughout the day. Also, since the sun is a point source that follows a particular sun path, direct irradiation on different flats varies more noticeably and therefore its heating effect is more acute and perceivable.

As for the correlation between night-time thermal sensation and solar irradiation on windows, a medium size effect was found in TP Court Block but no significant result was found in CM Point Tower. The lack of effect on the

latter is believed to be due to the cooling effect of wind, which is supported by findings to be described in sections 3.3 and 3.4.

Table 2: Correlations between solar irradiation on windows of major uses vs. thermal sensations and sunlight perceptions

		CM Point Tower			TP Court Block		
		Thermal comfort during day time	Thermal comfort during night time	Perceived sunlight	Thermal comfort during day time	Thermal comfort during night time	Perceived sunlight
direct solar irradiation per floor area	Correlation	.328**	.188	.417**	.390**	.257*	.389**
	Coefficient Sig. (1-tailed)	.005	.075	.000	.001	.024	.001
diffuse solar irradiation per floor area	Correlation	.024	-.086	-.034	.080	.058	.112
	Coefficient Sig. (1-tailed)	.429	.258	.398	.271	.330	.197
direct & diffuse solar irradiation per floor area	Correlation	.185	.020	.135	.226*	.148	.263*
	Coefficient Sig. (1-tailed)	.079	.438	.152	.041	.130	.021

* Significant at .05 level (1-tailed) ** Significant at .01 level (1-tailed)

Effect on electricity consumption

Parametric correlation analyses were conducted between solar irradiation on major windows (direct, diffuse and direct-plus-diffuse) and average electricity consumption of a flat. No significant correlation was found for two possible reasons. First, the significant effect of solar irradiation were mainly found in day time when most occupants were not at home and only 10% of air-conditioning usage occurred (based on survey results). Therefore, the day-time thermal discomfort due to sunlight was not translated to higher air-conditioning usage. Second, non-climatic factors such as occupants' habit on the use of air-conditioners and the efficiency of the machines weakened the link between air-conditioning usage and electricity consumption. It further masked the overall correlation between solar irradiation and electricity consumption.

3.2 Relationships between simple geometrical measurements, indoor thermal environment and electricity consumption

3.2.1 Effects of flat orientation

Flat orientation was the orientation that the principal façade of a flat faces. The principal façade was defined as the façade with the largest window area of major rooms, with the exception of CM Point Tower in which the four corner units were defined as facing northeast, southeast, southwest and northwest. Flat orientations were grouped into eight categories, which were defined by dividing the azimuth into 8 equal sectors with their mid-points pointing towards due north (N), northeast (NE), east (E) etc. It is worth noticing that all west-facing flats in

TP Court Block and TP Large Court are exclusively installed with horizontal sun-shading device. Therefore, any adverse effect of west-facing on indoor thermal comfort is likely to be even greater if no sun-shading device is installed.

Effect on daytime and night-time thermal comfort

Figure 2 shows the daytime and night-time thermal comfort of respondents living in flats that face different orientations. A noticeably higher thermal discomfort was found in west-facing flats both in day time and at night. In addition, a relatively low thermal discomfort of respondents living in flats facing south and southeast was expressed in day time. A marginally lower night-time thermal discomfort was also expressed by respondents living in flats facing south, southeast, and northeast.

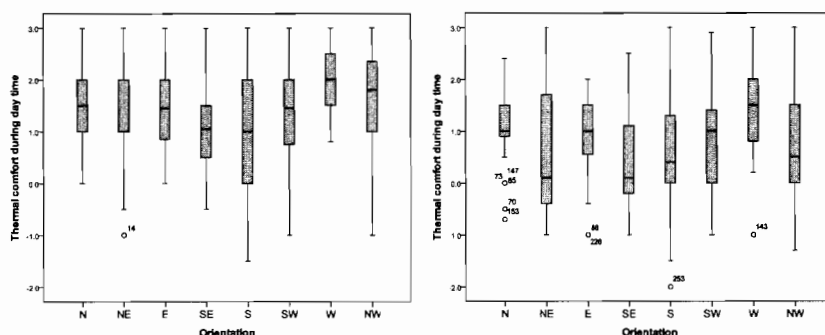


Figure 2: Thermal comfort of respondents in flats facing different orientations – all building groups (left: daytime; right: night-time)

Based on results from non-parametric tests, daytime thermal comfort was shown to be significantly affected by the orientation of the flat, $H(7)=17.9$, $p<.05$. However, post-hoc analyses showed that the significant differences were only found when the high thermal discomfort in west-facing flats was compared with the low thermal discomfort in south- and southeast-facing flats. While west-facing flats are shown to be significantly hotter than south- and southeast-facing flats, their thermal environments are not significantly different from the average condition.

The night-time thermal comfort was also shown to be significantly affected by flat orientation, $H(7)=18.0$, $p<.05$. In this case, post-hoc analyses showed that west-facing flats were perceived as significantly hotter than the average condition. However, south- and southeast-facing flats (the two coolest orientation groups) were only shown to be cooler than west-facing flats but not the average condition.

Difference between CM Point Tower and TP Court Block

Separate analyses on CM Point Tower and TP Court Block reaffirmed some of the above findings. In CM Point Tower, respondents living in west-facing flats (NW and SW) expressed a significantly higher daytime and night-time

thermal comfort than other respondents as shown in Figure 3. The same difference was also observed in TP Court Block. However, the lower thermal discomfort in south-facing flats was only found in TP Court Block but not CM Point Tower. In CM Point Tower, no significant difference was found between the thermal comfort in south-facing flats and north-facing flats either in day time or at night. In TP Court Block, on the contrary, noticeably lower thermal discomfort was generally found in south- and southeast-facing flats, which is likely to be attributable to the combined effect of lower solar irradiation and higher air circulation. The survey was performed in July when the sun crossed the sky vault on the north. South-facing flats were therefore subject to less solar heat gain than their north-facing counterparts. In addition, the prevailing wind direction is south/southeast in July in Singapore (Meteorological Services Division, 2009), which enhances the cooling potential of south-facing flats by natural ventilation. The lack of effect in CM Point Tower is believed to be due to the availability of east- and west-facing side windows, which moderated the difference in the thermal environment between north-facing and south-facing flats by facilitating effective cross-ventilation.

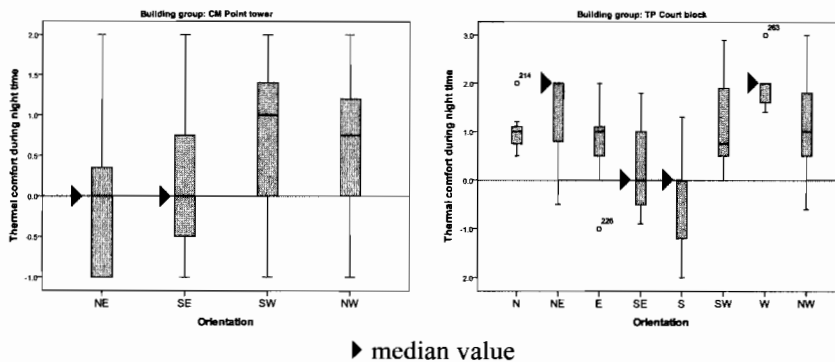


Figure 3: Night-time thermal comfort in flats facing different orientations (left: CM Point Tower; right: TP Court Block)

Effect of electricity consumption

Parametric tests showed that there are significant differences in average monthly electricity consumption (when controlled for non-built form related factors) between flats facing different orientations, $F(7,207)=3.009$, $p<.05$. However, post-hoc study shows that the effect of flat orientation was statistically significant only when the two extremes were compared. As shown in Figure 4 on the left, west- and east-facing flats tend to consume more electricity while south- and southwest-facing flats tend to consume less. Comparing to the mean monthly electricity consumption of all flats with non-built form related factors controlled (370kWh), west-facing flats consumed 122kWh (33%) more electricity per month on average. As mentioned in 3.2.1, additional sun-shading devices had already been installed exclusively for west-facing flats in two building groups, without which the effect of west-facing is expected to further

increase. The high electricity consumption in west-facing flats is likely to be due to the combined effect of the lack of prevailing wind throughout the year and the strong solar radiation from the west in the afternoon. With the building thermal mass, the effect of the latter is carried on to the evening when most household members return home and air conditioning is more likely to be used.

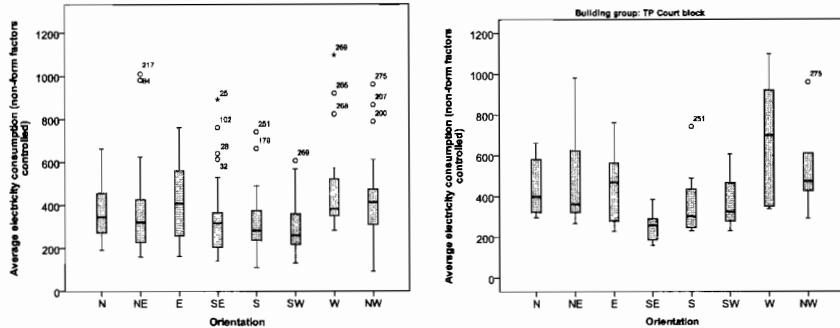


Figure 4: Average electricity consumption controlled for non-built form related factors (kWh) vs. flat orientation (left: all building g groups; right: TP Court Block)

Difference between CM Point Tower and TP Court Block

The significantly higher electricity consumption of west-facing flats was found in TP Court Block but not CM Point Tower. In CM Point Tower, parametric tests showed that there is no significant difference in average electricity consumption between flats facing different orientations, $F(3,48)=.562$, n.s. even though nearly half of the flats have windows facing due west. This is believed to be due to superior air circulation in those flats and therefore relatively moderate median thermal discomfort (approx. +1 in CM Point Tower versus approx. +2 in TP Court Block) that led to less cooling energy consumption. On the contrary, difference in electricity consumption between west-facing flats and other flats is more apparent in TP Court Block as shown in Figure 4 on the right. The larger difference is believed to be due to the particularly low air circulation in TP Court Block, which did not allow the daytime solar heat gain to dissipate effectively in the evening when the air conditioning was most intensively used.

3.2.2 Effect of vertical position and sky view factor

To investigate whether these two simple geometric descriptors can be used to assess the impact of urban geometry on the indoor thermal environment, correlation analyses were performed on 110 combinations between simple geometric descriptors, building groups, environmental performance indicators and orientation groups as listed in Table 3. CM Point Tower was separately studied because it is substantially taller and more exposed to the sky than other three building groups. Any significant result may represent the difference

between CM Point Tower and other building groups instead of the geometric descriptors under investigation.

Table 3: 110 scenarios tested for significant correlations between simple geometric descriptors and environmental performance indicators

Simple geometric descriptors	Environmental performance indicators	Building group	Orientation groups
▪ Vertical position ▪ Sky view factor	▪ Daytime thermal comfort ▪ Night-time thermal comfort ▪ Perceived sunlight ▪ Perceived air circulation ▪ Average electricity consumption	▪ All groups except CM Point Tower ▪ CM Point Tower ▪ TP Court Block	▪ On aggregate ▪ On the 8 individual orientation groups*

* applied to "all group except CM Point Tower" only. Flats in other two building groups were not test due to the small number of flats facing each orientation.

A series of correlation analyses showed that neither the vertical position nor the sky view factor of flats had consistent effects on the indoor thermal environment or other environmental perceptions. Among the 110 scenarios, only three statistically significant correlations were found. Without strong theoretical reason for distinguishing them from the rest, these correlations offer little predictive power to future assessments. It shows that neither the vertical position of flats nor the sky view factor serves as a good indicator for the indoor thermal environment or cooling load of a flat in a high-density tropical context.

3.3 Comparison between building groups representing different urban-form prototypes

The survey found noticeable differences between the four groups in night-time thermal comfort, electricity consumption, perceived sunlight and perceived air circulation. At the same time, no noticeable differences were found in daytime thermal comfort and humidity. As shown in figures 5 and 6, CM Point Tower differs from other building groups by having a noticeably lower night-time thermal discomfort, higher perceived sunlight and higher perceived air circulation. TP Court Block, on the other hand, is shown to have a noticeably lower perceived air circulation and higher electricity consumption (by 23%). All these differences were found to be statistically significant. The distinctive morphological characteristics of each building groups provide plausible reasons for the differences in environmental conditions, which will be further explored in Section 4.

Further comparisons between the figures suggest that both night-time thermal comfort and electricity consumption exhibit stronger links with perceived air circulation than perceived sunlight. Respondents in CM Point Tower expressed higher perceptions to both sunlight and air circulation, and on aggregate they generally felt cooler. On the other hand, respondents in TP Court Block perceived similar amount of sunlight but less air circulation, and on aggregate

they consume significantly more electricity. The ultimate indoor thermal comfort and electricity consumption therefore appear to be more influenced by perceived air circulation than by perceived sunlight.

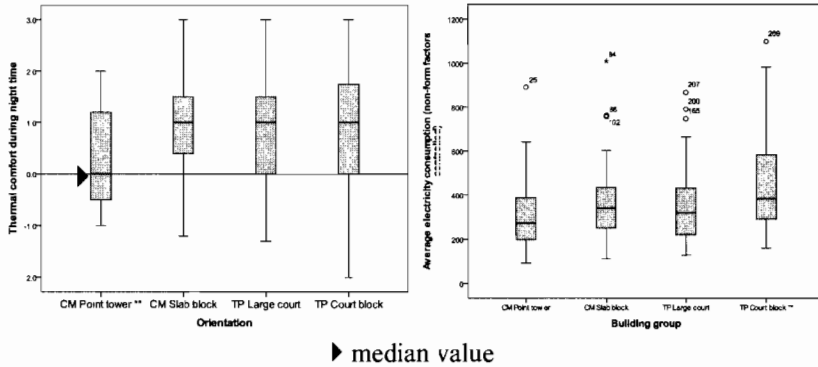


Figure 5: Night-time thermal comfort (left) and average electricity consumption (controlled for non-built form related factors) (right) in different building groups

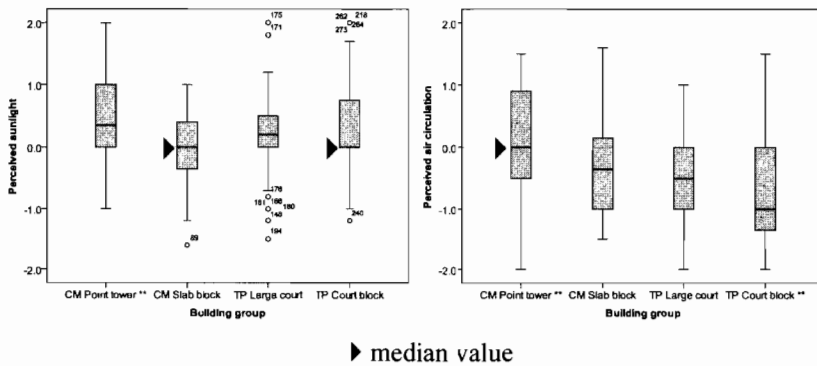


Figure 6: Perceived sunlight (left) and air circulation (right) in different building groups

3.4 Relationship between perceived environmental factors, thermal comfort and electricity consumption

As shown in previous sections, variations in urban geometry often result in opposing effects on sunlight and air circulation in terms of their effects on indoor thermal environment. To understand the relative effect of these environmental factors, correlation analyses were performed to compare the effects of perceived sunlight, air circulation and humidity on daytime thermal comfort, night-time thermal comfort and average electricity consumption. Daytime thermal comfort (the higher, the hotter) was found to be correlated negatively with perceived air circulation ($\sigma = -0.49$) and positively with perceived sunlight ($\sigma = 0.19$) and perceived humidity ($\sigma = 0.55$). On the other hand, night-time thermal comfort

was found to be correlated negatively with perceived air circulation ($\sigma = -0.43$) and positively with perceived humidity ($\sigma = 0.47$). In both cases, the effects of air circulation and humidity were comparable and were much larger than sunlight, which agrees reasonably well with the relative effects of these environmental factors on thermal comfort as observed in a laboratory setting (Fanger, 1972).

For electricity consumption, none of the three environmental factors on indoor thermal comfort showed any significant effect. On the other hand, daytime and night-time thermal comfort respectively possess weak ($\sigma = 0.16$) and strong ($\sigma = 0.64$) correlations with electricity consumption. It implies that optimising one environmental factor alone is unlikely to result in cooling energy conservation. It also suggests that optimizing night-time rather than daytime indoor thermal comfort is more crucial to cooling energy conservation in the hot and humid climate.

4 Discussions and Conclusions

Design implications of findings

The study contributes to the knowledge of climate-responsive design for contemporary tropical cities by identifying the urban geometric features that influence the indoor thermal environment and cooling load of high-density housing in the hot and humid climate. Both flat orientation and direct solar irradiation on windows of major rooms per floor area were shown to be effective indicators for the resulting indoor thermal comfort. While it is generally true that higher thermal discomfort was reported if the flat faced west or received more solar radiation, the strength of the effect depends the level of perceived air circulation. The correlation between direct solar irradiation and night-time thermal comfort, together with the significantly higher electricity consumption of west-facing flats, was only found in TP Court Block but not CM Point Tower. This is believed to be attributable to the superior air circulation of flats in CM Point Tower, which moderated or even outweighed the adverse effect of solar heat gain.

Furthermore, between the four surveyed building groups that represent distinctive urban-form prototypes, there are significant differences in night-time thermal comfort, perceived sunlight, perceived air circulation and the electricity consumption of flats. For example, CM Point Tower is characterised by its great building height (25 storeys) and low site coverage (Figure 1), which creates an urban geometry with higher exposure to wind and sunlight. Each flat also has its windows of major rooms facing two orientations, which facilitates cross-ventilation (Figure 7). These physical attributes have possibly resulted in a superior night-time thermal comfort level whilst retaining an average daytime thermal comfort level. It suggests that the favourable effect of higher exposure to wind outweighed the adverse effect of higher exposure to sunlight. Building clusters that have a high building height and low site coverage like CM Point

Tower potentially offer a climate-responsive prototype for high-density housing in the hot and humid climate.

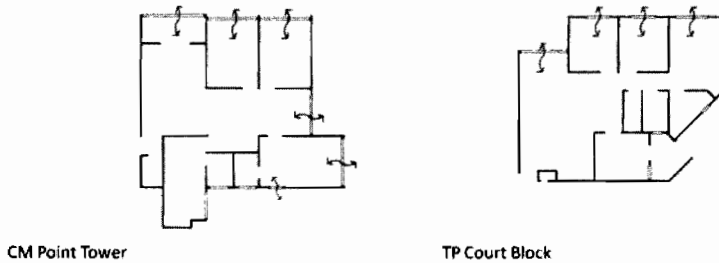


Figure 7: Ventilation potential of typical flats in CM Point Tower and TP Court Block (blue arrow: windows in major rooms)

TP Court Block, on the contrary, has a low height profile (10 storeys) and a more enclosed urban form (Figure 1). Each flat also has low cross-ventilation potential since all major windows face the same orientation (Figure 7). Respondents in this building group perceived significantly weaker air circulation and an average level of sunlight. At the same time, they were generally found to have higher air-conditioning usage and average electricity consumption (23% higher than average). This suggests that building clusters with semi-enclosed open space and mono-directional windows in each flat like TP Court Block potentially consume greater cooling energy in high-density housing in the hot and humid climate.

The significance of air circulation over sunlight becomes even more apparent when the pattern of occupancy is considered. Based on the survey result, 71% of occupancy hours are found between 7pm to 7am when no sunlight is available. Therefore, the mere consideration of reducing solar irradiation on building facades does not benefit the indoor thermal environment at the most critical time. Maximising wind potential, on the contrary, can enhance the indoor thermal comfort in the evening when most people are at home and air-conditioners are actively used.

Despite their relationships with the exposure of a flat to the ambient climate in theory, the vertical position of flats and the average sky view factors of windows are found to be poor indicators of perceived indoor thermal conditions and electricity consumption. It is therefore not advisable to use these descriptors to evaluate the indoor thermal environment of high-density tropical housing. On the other hand, simulated direct solar irradiation on major windows was found to correlate significantly with daytime thermal comfort and perceived sunlight, and was shown to correlate much stronger than direct-plus-diffuse irradiation. Therefore, simulated direct solar irradiation provides an adequate indicator for evaluating the effect of an urban or building design on solar heat gain in the conceptual design stage.

Limitation of the research

Numerous assumptions and approximations have been made in both simulating solar irradiation on windows and evaluating the environmental conditions in a flat. Major ones include the use of TMY weather data to approximate the actual distribution of sky radiance, the use of solar irradiation on windows to approximate the effect of solar heat gain, and the use of respondents' perception to represent the levels of sunlight, air circulation and humidity inside a flat. Nonetheless, significant findings in this study show good agreements with theoretical relationships, which give confidence to the validity of the research method. First, simulated solar irradiation based on the aggregate sky was shown to have significant effects on the indoor thermal comfort and perceived sunlight of respondents. Second, good agreements were found between the theoretical and empirical effects of sunlight, air circulation and humidity on thermal comfort. It is particular revealing that perceived sunlight was found to be significantly correlated with daytime but not night-time thermal comfort, which would occur only if respondents distinguished their daytime thermal comfort (question 2) and night-time thermal comfort (question 3) carefully when they responded. Third, solar irradiation is both a simulated and a perceived quantity in this study but air circulation is only represented by respondents' perceptions. The validity of using perceived air circulation to represent the actual indoor wind environment should be further investigated.

Further research

Based on the above discussion, two apparent follow-up research questions emerge. First, air circulation assessments in this study were solely based on residents' perceptions. Wind tunnel tests and/or computational fluid dynamics modelling can be employed to ascertain the urban geometric features that are favourable to indoor air circulation. Second, the actual design feature that causes the inferior air circulation in TP Court Block should be identified. The low air circulation in TP Court Block can be attributable to either its enclosed urban form or its mono-directional windows, or both. Singling out the design feature that causes the inferior air circulation will inform better design for high-density housing in the hot and humid climate.

Acknowledgements

The first author would like to express his gratitude to Dr. N H Wong and his colleagues in the Department of Building at the National University of Singapore for their valuable comments and administrative support on his field work in Singapore.

References

- Auliciems, A. (1981). Towards a psycho-physiological model of thermal perception. *International Journal of Biometeorology*, 25(2), 109-122.
- Compagnon, R. (2004). Solar and daylight availability in the urban fabric. *Energy and Buildings*, 36(4), 321-328.
- Fanger, P. O. (1972). *Thermal comfort: analysis and applications in environmental engineering* (p. 244). (New York): McGraw-Hill.
- Kubota, T., Miura, M., Tominaga, Y., & Mochida, A. (2008). Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. *Building and Environment*, 43(10), 1699-1708.
- Lam, J. C., Hui, S. C. M., & Chan, A. L. S. (1993). Overall thermal transfer value control of building envelope design Part 2 — OTTV parameters. *Hong Kong Engineer*, 21(9).
- Lam, J. C. (1996). An analysis of residential sector energy use in Hong Kong. *Energy*, 21(1), 1-8.
- Leung, K. S., & Steemers, K. (2009). Exploring solar-responsive morphology for high-density housing in the tropics. In *Proceedings of the International Conference on Solar Energy Applications to Buildings 2009 (CISBAT 2009)*. Presented at the International Conference on Solar Energy Applications to Buildings 2009 (CISBAT 2009), Switzerland.
- Lucas Souza, L. C., Pedrotti, F. S., & Leme, F. T. (2004). Urban geometry and electrical energy consumption in a tropical city. Presented at the Fifth Conference on Urban Environment, Vancouver, Canada.
- Meteorological Services Division. (2009). *Weatherwise Singapore*. Singapore: National Environmental Agency.
- Ng, E., Chan, T., Cheng, V., Wong, N. H., & Han, M. (2006). Designing high density cities - parametric studies of urban morphologies and their implied environmental performance. In J. Bay & B. L. Ong (Eds.), *Tropical sustainable architecture - social and environmental dimensions* (pp. 151-180). Elsevier.
- Perez, R., Seals, R., & Michalsky, J. (1993). All-weather model for sky luminance distribution--Preliminary configuration and validation. *Solar Energy*, 50(3), 235-245.
- Roth, M. (n.d.). FASS Weather Report. Retrieved November 23, 2009, from http://nt2.fas.nus.edu.sg/geog/weather_archive_data_frame.asp.
- U.S. Department of Energy. (2008). EnergyPlus: Weather Data. http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm.
- Wong, N. H., Feriadi, H., Lim, P. Y., Tham, K. W., Sekhar, C., & Cheong, K. W. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore. *Building and Environment*, 37(12), 1267-1277.