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Outdoor thermal comfort in sub-tropical climate: A longitudinal study based in Hong Kong

Vicky Cheng[2], Edward Ng[1], Baruch Givoni[3]
[1] Department of Architecture, Chinese University of Hong Kong, Hong Kong
[2] Department of Architecture, University of Cambridge, UK
[3] Department of Architecture, UCLA, USA

ABSTRACT
In sub-topical city of Hong Kong where summer is hot and humid, the usage of outdoor spaces is often hindered due to thermal discomfort. In order to improve the thermal comfort of the outdoor environment and to make urban outdoor spaces delightful places for people to use and enjoy, better understanding of the thermal perception of people in different climatic conditions is needed. This paper presents the results of a longitudinal outdoor thermal comfort study conducted in Hong Kong. The findings of the study reveal that air temperature, wind speed and solar radiation intensity are the most influential factors in determining the thermal sensation of people. Based on the data collected, a predictive formula for estimating the subjective outdoor thermal sensation has been developed. In accordance to the formula, under typical summer conditions in Hong Kong, a wind speed of 1.6 m/s is needed for a person in light clothing sitting under shade to achieve neutral thermal sensation.

KEYWORDS
Outdoor Comfort, Thermal Comfort, Wind, Longitudinal, Hong Kong

1. INTRODUCTION

This paper presents a longitudinal outdoor thermal comfort study conducted in Hong Kong as part of the Wind for Comfort study within the scope of the "Feasibility study for establishment of air ventilation assessment system" (AVAS) in 2003 (Ng, 2004) and a follow-up study entitled "Urban climatic map and standards for wind environment – feasibility study" (UCMap) in 2006 (Ng et al., 2006). The outcome may provide some useful insights for planners, architects and engineers to better optimize air ventilation for Hong Kong; and by and large shed light on the urban wind comfort issues in high density sub-tropical cities.

2. OUTDOOR THERMAL COMFORT STUDIES

Outdoor thermal comfort has attracted wide attention in the last decade (Ahmed, 2003, Nikolopoulou and Lykoudis, 2006; Cheng and Ng, 2006; Spagnolo and de Dear, 2003). These studies were mostly conducted by means of transverse questionnaire surveys, where a large number of subjects were interviewed in different environmental conditions. Based on this method, the responses gathered can provide a statistical estimated thermal sensation of an average person under static climatic condition.

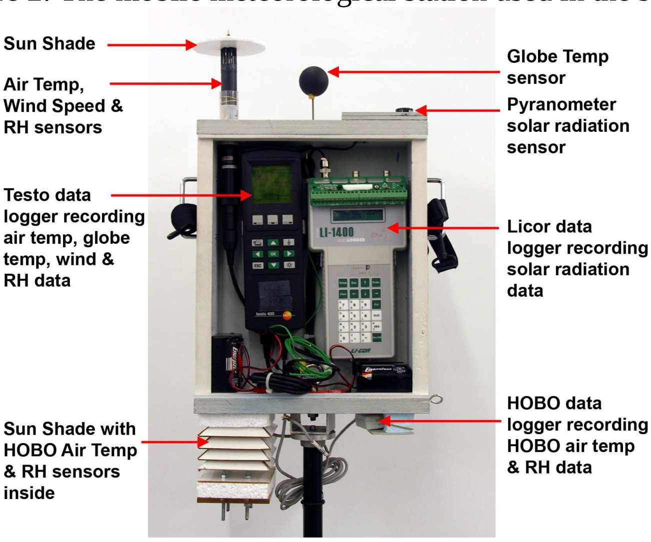
Nevertheless, in terms of predicting thermal sensation under changing climatic conditions, this method represents certain fundamental limitations. Since each subject was sampled once only; and his or her thermal sensation was captured under a relatively static climatic condition during the survey. The transverse approach cannot reflect the effect of changing climatic conditions, increased wind speed for example, on thermal sensation. In order to understand the genuine changes in thermal sensation over different climatic conditions, the effects of individual differences need to be removed. The longitudinal approach can serve this purpose. In a longitudinal experiment, the thermal sensations of a relatively small number of subjects over different environmental conditions are followed and evaluated. As such, the thermal sensation that changes over different climatic conditions can be observed. The method has been adopted in a couple of studies conducted in Japan and Israel (Givoni et al., 2003, Uchida et al., 2009).

3. METHOD OF STUDY

The experiment was conducted in an open plaza on the campus of The Chinese University of Hong Kong. Four experimental conditions were set up for the study (Figure 1). The microclimatic condition in each experimental setting was measured using a mobile meteorological station (Figure 2). The meteorological station included sensors for measuring air temperature, globe temperature, wind speed, relative humidity and solar radiation. Wind speed, air temperature and relative humidity are measured using TESTO 3-function probes. Globe temperature is measured by tailor-made globe thermometer, which consists of a thermocouple wire (TESTO flexible Teflon Type K) held at the middle of a 38mm diameter black table-tennis ball. The construction of these globe thermometers was made with reference to prior studies to improve the response time (Humphreys, 1977, Nikolopoulou et al., 1999). Solar radiation was measured using standard pyranometer (LICOR LI-200SA). During the experiment, each set of instruments was mounted on a camera tripod adjusted to the height of the body of the subjects in sitting position.

Figure 1: Set up of the four experimental climatic conditions

Figure 2: The mobile meteorological station used in the study



The subject group consisted of eight participants, in which half were males and half were females. For each gender group, half of the subjects were of age 20s and half were of age 50s. The eight subjects worked in four pairs in the experiment which consisted of a series of experimental sessions. In each session, each pair was instructed to sit still in one of the experimental settings for 15 minutes. Subsequently, each subject was asked to complete a thermal comfort questionnaire. They had 10 minutes to complete the questionnaire and rest before moving on to the next experimental settings (Figure 3). The procedures were repeated until each pair has completed all the four experimental settings.

Figure 3: Illustration of the experimental procedures

The questionnaires dealt with the subjects' sensations with regard to the microclimatic conditions and their overall comfort. The subjective sensation votes included rating of the thermal environment on a 7-point scale, solar intensity on 3-point scale, wind speed on 7-point scale, humidity of air on 3-point scale and wetness of skin on 5-point scale. The overall comfort was rated on a four-point scale from -2 (very uncomfortable) to +2 (very comfortable).

Three longitudinal experiments were conducted in 2006: two were carried out in summer and one in winter. The weather conditions on the days of the summer experiments were fairly typical Hong Kong summer climate; whilst the winter experiment day was slightly cooler than normal (Table 1). Each experiment consisted of three experimental sessions, which were carried out in three different periods of the day (morning, afternoon and evening). Total 288 questionnaires were received in which two of them were discarded due to missing data. Eventually, 286 questionnaires were included in the data analysis.

Table 1: Summary of weather conditions on the days of experiments

	Summer - August			**Winter - December**	
	Day 8th	Day 19th	30-year Average	Day 19th	30-year Average
Temperature (°C)					
Average	28.5	27.6	28.4	16.1	17.6
Maximum	31.1	29.8	31.3	18.9	20.5
Minimum	26.1	24.3	26.3	13.1	15.4
Relative Humidity (%)	80	81	81	60	68
Solar Radiation (W/m^2)	514	523	499	479	341

Data source: Hong Kong Observatory – monthly weather summary

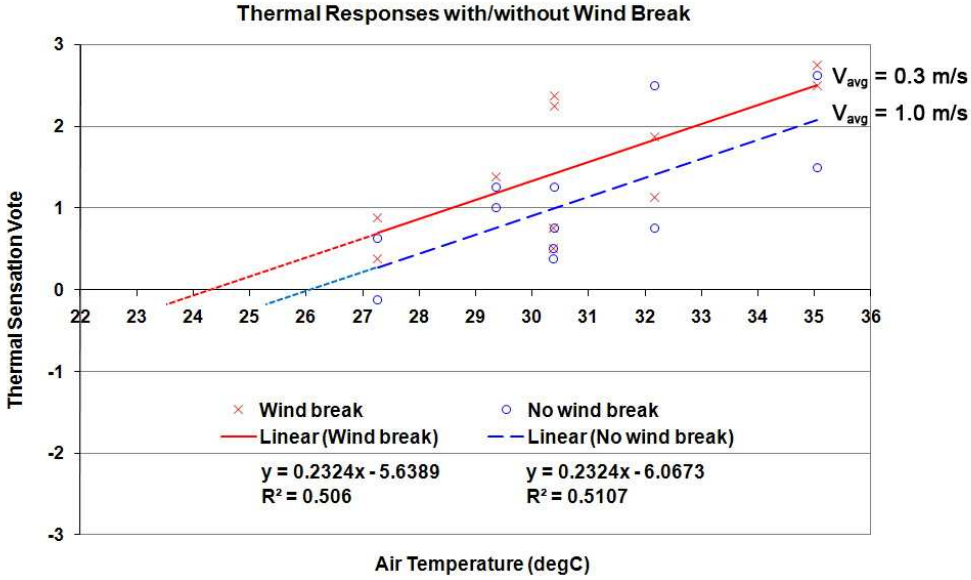
4. RESULTS OF THE STUDY

4.1 The effect of changing wind conditions

Figure 4 shows the effect of changing wind conditions on the thermal sensation of subjects in summer, as a function of air temperature and with corresponding regression lines. The average wind speeds in settings with and without wind break are about 0.3 m/s and 1 m/s respectively. According to the regression lines, given the same air temperature, the subjects rated the settings with wind break about 0.43 units hotter than the settings without wind break. The subjects generally rated the overall wind conditions during the experiments as less than appropriate. The wind conditions were rated as too still in settings with wind break and slightly still without wind break.

In both settings with and without wind break, the average slope of thermal sensation to air temperature is 0.23 units/°C. The difference in thermal sensation between the two settings is 0.43 units. Thus, it can be inferred that the effect of increasing wind speed from 0.3 m/s to 1 m/s is equivalent to a drop of about 1.9°C in air temperature. This appears to parallel the findings of a ventilation and comfort study conducted in Thailand where a 2°C rise in comfort temperature was observed for an increase of wind speed in this range (Khedari et al., 2000). By extrapolating the regression lines to the x-axis, the neutral air temperatures can be determined. According to Figure 4, the neutral air temperature at 0.3 m/s wind speed is about 24.2°C. When the wind speed is increased to 1 m/s, a higher neutral air temperature of 26.1°C is obtained.

Figure 4: Effects of changing wind conditions on thermal sensation in summer



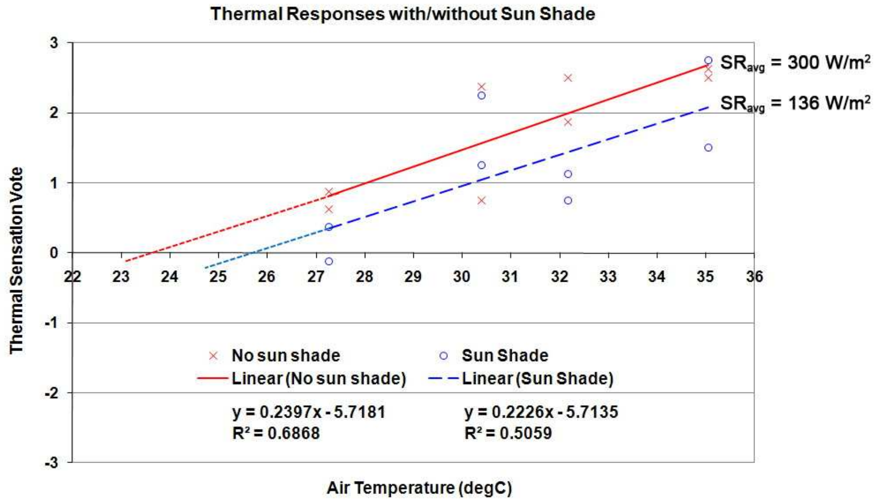
Similar analysis was conducted with the winter data. The average wind speeds in settings with and without wind break are about 0.2 m/s and 0.9 m/s respectively, which are comparable to the summer wind speed range. The subjects generally felt cooler in settings with higher wind speed. However, no obvious trend is observed between thermal sensation and air temperature with respect to different wind conditions. This may suggest that the effect of changing wind conditions is less significant in winter than summer. Nonetheless, the insignificant results may also due to the smaller dataset available for the winter analysis.

4.2 The effect of changing solar radiation conditions

Figure 5 shows the effect of changing solar radiation conditions on the thermal sensation of subjects in summer, as a function of air temperature and with corresponding regression lines. The average solar radiation intensities in settings with and without sun shade are about 136 W/m^2 and 300 W/m^2 respectively. According to the regression lines, given the same air temperature, the subjects rated the settings without sun shade about 0.55 units hotter than the settings with sun shade. The subjects under sun shade on average rated the solar exposure condition as just fine. When under direct sun exposure, they generally rated the solar exposure condition as slightly too much.

In both settings with and without sun shade, the average slope of thermal sensation to air temperature is about 0.23 units/^{o}C. The difference in thermal sensation between the two settings is 0.55 units. Thus, it can be inferred that the effect of increasing solar radiation from 136 W/m^2 to 300 W/m^2 is equivalent to an increase of about 2.4^{o}C in air temperature. Rigidly speaking, the regression lines are not exactly parallel to each other but diverge towards high temperature. In other words, higher temperature enhances the effect of solar radiation. By extrapolating the regression lines to the x-axis, the neutral air temperature at 300 W/m^2 solar intensity is found to be about 23.5^{o}C. When the solar intensity is reduced to 136 W/m^2, a higher neutral air temperature of about 25.7^{o}C is obtained.

Figure 5: Effects of changing solar radiation conditions on thermal sensation in summer



Similar analysis was conducted with the winter data. The average solar intensities in settings with and without sun shade are about 135 W/m^2 and 452 W/m^2 respectively. The shaded condition is similar whilst the unshaded condition is moderately higher than the summer ones. The subjects generally felt warmer in settings with higher solar intensity. However, no obvious trend is observed between thermal sensation and air temperature with respect to different solar radiation conditions. This may suggest that the effect of changing solar radiation conditions is less significant in winter than summer. As aforementioned, the insignificant results may also due to the smaller dataset available for the winter analysis.

4.3 Physiological Equivalent Temperature

Physiological equivalent temperature (PET) is a thermal index derived from the Munich Energy Balance Model for Individual (MEMI) – a heat balance model of human body. It is defined as equivalent to the air temperature in a typical indoor setting at which, the heat balance of the human body is maintained, with core and skin temperatures equal to those under the conditions being assessed. Thus, PET enables us to compare the integral effects of complex thermal conditions outdoors with our experience indoors (Hoppe, 1999, Matzarakis et al., 1999).

The calculation of PET assumes constant values for clothing (0.9 clo) and activity (work metabolism of 80W plus basic metabolism). Hence, it is independent of individual behaviour and provides objective evaluation of the sole effect of climate on the thermal state of the body. However, since our actual thermal sensations heavily rely on individual characteristics. PET in this sense cannot be readily used as an indication of thermal comfort as long as its relationship with actual thermal sensation is established. The data collected in our experiments provide a basis for a better understanding of this matter.

Figure 6 and Figure 7 show the correlations between the actual thermal sensation vote and PET in summer and winter respectively. According to the regression lines, the neutral PET in summer (25^{o}C) is higher than winter (21^{o}C). This appears to suggest that people accept higher temperature in summer compares to winter. In other words, our thermal sensation varies with the prevailing climatic conditions. Table 2 shows the values of PET at different levels of thermal sensation.

Figure 6: Correlation between actual thermal sensation votes and physiological equivalent temperature (PET) in summer

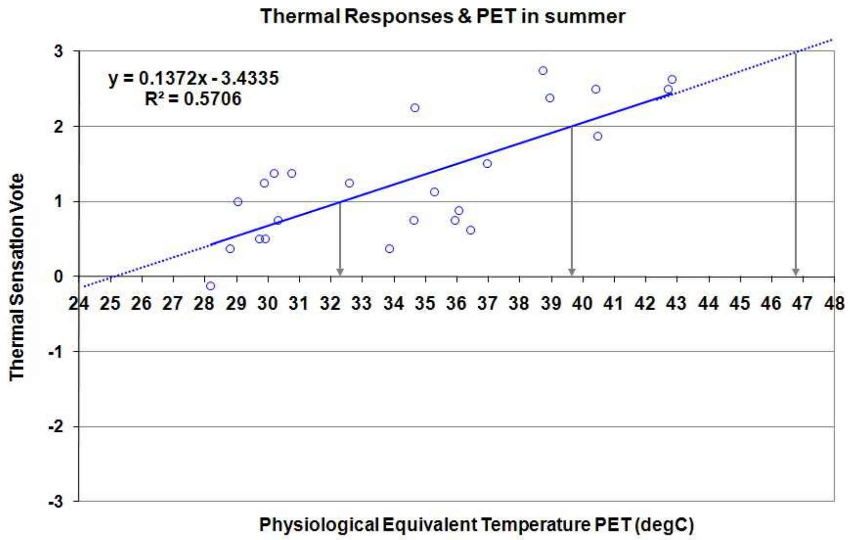


Figure 7: Correlation between actual thermal sensation votes and physiological equivalent temperature (PET) in winter

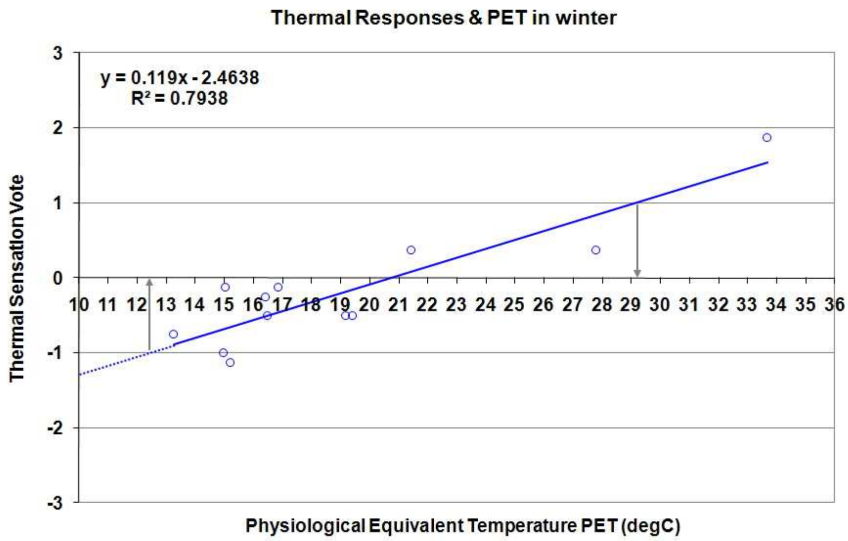


Table 2: Physiological equivalent temperature (PET)
at different levels of thermal sensation

Thermal sensation		Physiological equivalent temperature (PET)	
		Summer (°C)	Winter (°C)
-1	Slightly cool	-	12.3
0	Neutral	25.0	21.0
1	Slightly warm	32.2	29.2
2	Warm	39.7	-
3	Hot	46.8	-

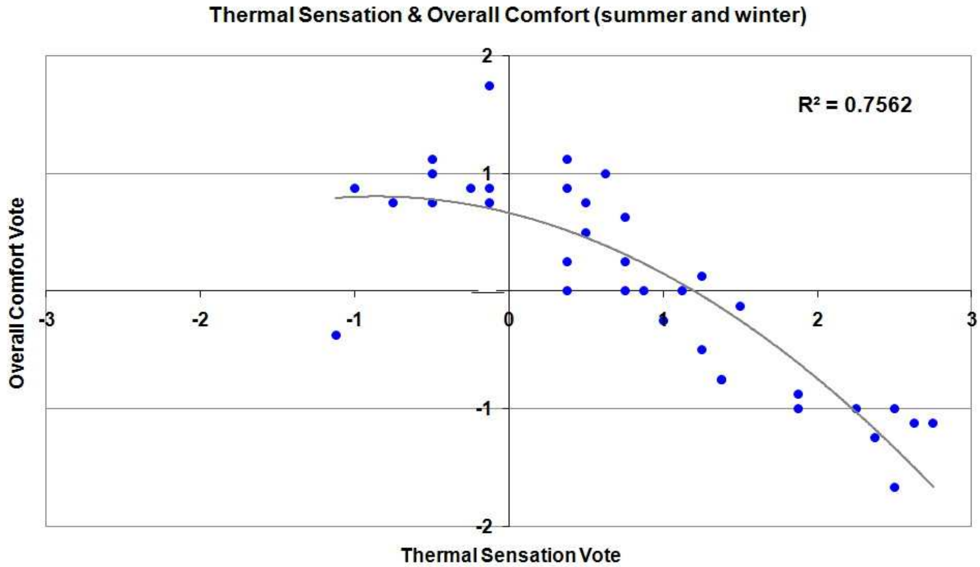
The neutral PETs obtained in this study appears to meet the findings obtained in the outdoor thermal comfort transverse survey, which was also conducted in Hong Kong as part of the UCMap project (Ng et al., 2008). The transverse survey consists of 2700 samples was carried out in three different types of environment covering streets, housing estates and urban parks. The overall mean and median neutral PETs obtained in summer are 27°C and 29°C respectively. The neutral PETs however vary between different types of environment. The mean and median neutral PETs are 27°C and 28°C for streets; 29°C and 30°C for housing estates; and 26°C and 24°C for urban parks. The neutral PETs obtained in parks are significantly lower than other environments. This is because ambient air temperature is an important variable in the PET model; provided that all other input variables stay constant, PET increases with increasing air temperature. Parks are generally cooler than other urban spaces. This results in a lower range of PETs and thus a potentially lower neutral PET. The longitudinal experiment was taken place in an open plaza which resembles an urban park. The neutral PET (25°C) obtained in the longitudinal experiment parallels the neutral PETs obtained in parks from the transverse survey (24-26°C).

Cooler neutral PETs are obtained in winter; the mean and median obtained in the transverse survey are 19°C and 20°C respectively. This is comparable to the winter neutral PET (21°C) obtained in the longitudinal experiment.

4.4 Thermal sensation and overall comfort

Conventionally neutral thermal sensation (TS=0) is supposed to correspond to the state of thermal comfort. This assumption is tested in our experiment. Figure 8 shows a scatter plot of overall comfort against thermal sensation comprising both summer and winter data. Overall comfort is rated on a 4-point scale from -2 (very uncomfortable) to +2 (very comfortable). The middle point zero was deliberately taken out from the scale for reasons explained in the methodology section.

Figure 8: Scatter plot of overall comfort against thermal sensation



Overall comfort exhibits strong correlation with thermal sensation and as one would expect, the correlation is non-linear. The subjects felt uncomfortable in hot conditions (TS>2) but the overall comfort gradually increases as the thermal conditions approaching neutral. The subjects generally felt comfortable within the range between slightly warm (TS=1) and slightly cool (TS=-1). According to Table 2, this is equivalent to a neutral PET up to 32°C in summer and down to 12°C in winter. Although there is not enough data beyond the slightly cool condition, the trend line in Figure 8 seems flatten out and likely to go downward in cooler conditions. The results appear to back the assumption that neutral thermal sensation corresponding to comfort.

5. CONCLUSION

This paper presents the findings of an outdoor thermal comfort study conducted in Hong Kong using longitudinal experiments, an alternative approach to the conventional transverse surveys. The results show that changing wind speeds have significant influences on thermal sensation, especially in summer. An initial analysis of the effects of wind and solar radiation on thermal sensation in summer shows that: 1) an increase of wind speed from 0.3 m/s to 1 m/s is equivalent to a drop of about 2°C in air temperature.

The paper illustrates the use of physiological equivalent temperature (PET) as an alternative thermal index and establishes its correlation with actual thermal sensation. According to the results, the neutral PETs in summer and winter are 25°C and 21°C respectively. This finding corresponds to an urban park-like environment. The neutral PETs appear to vary in different types of environments.

The paper reveals a high correlation between thermal sensation and overall comfort. The subjects generally felt comfortable within the range between slightly warm (TS=1) and slightly cool (TS=-1). This is equivalent to a neutral PET up to 32^{o}C in summer and down to 12^{o}C in winter. Our findings support the assumption that neutral temperature corresponding to thermal comfort.

7. ACKNOWLEDGEMENT
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8. REFERENCES

AHMED, K. S. (2003) Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments. *Energy and Buildings,* 35**,** 103-110.

CHENG, V. & NG, E. (2006) Thermal comfort in urban open spaces for Hong Kong. *Architectural Science Review,* 49.3**,** 236-242.

FANGER, P. O. (1972) *Thermal Comfort,* New York, McGraw-Hill Book Co.

GIVONI, B., NOGUCHI, M., SAARONI, H., POCHTER, O., YAACOV, Y., FELLER, N. & BECKER, S. (2003) Outdoor comfort research issues. *Energy and Buildings,* 35**,** 77-86.

HOPPE, P. (1999) The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology,* 43**,** 71-75.

HOPPE, P. (2002) Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings,* 34**,** 661-665.

HUMPHREYS, M. A. (1977) The optimum diameter for a globe thermometer for use indoors. *Building Research Establishment Current Paper,* 9/78**,** 1-5.

KHEDARI, J., YAMTRAIPAT, N., PRATINTONG, N. & HIRUNLABH, J. (2000) Thailand ventilation comfort chart. *Energy and Buildings,* 32**,** 245-249.

MATZARAKIS, A., MAYER, H. & IZIOMON, M. G. (1999) Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology,* 43**,** 76-84.

NG, E. (2009) Policies and technical guidelines for urban planning of high density cities - Air Ventilation Assessment (AVA) of Hong Kong. *Building and Environment,* 44**,** 1478-1488.

NG, E., CHENG, V. & CHAN, C. (2008) Urban Climatic Map and Standards for Wind Environment - Feasibility Study. Technical Input Report No.1: Methodologies and Findings of User's Wind Comfort Level Survey. Hong Kong Planning Department.

NG, E., KWOK, K., SUN, D., YAU, R. & KATZSCHNER, L. (2006) Inception Report - Urban Climate Map and Standards for Wind Environment - Feasibility Study.

Technical Report for Planning Department HKSAR. Hong Kong Planning Department.
NG, E., TAM, I., NG, A., GIVONI, B., KATZSCHNER, L., KWOK, K., MURAKAMI, S., WONG, N. H., WONG, K. S., CHENG, V., DAVIS, A., TSOU, J. Y. & CHOW, B. (2004) Final Report - Feasibility Study for Establishment of Air Ventilation Assessment System. Technical Report for Planning Department HKSAR. Hong Kong Planning Department.
NIKOLOPOULOU, M., BAKER, N. & STEEMERS, K. (1999) Improvements to the globe thermometer for outdoor use. *Architectural Science Review,* 42**,** 27-34.
NIKOLOPOULOU, M., BAKER, N. & STEEMERS, K. (2001) Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy,* 70**,** 227-235.
NIKOLOPOULOU, M. & LYKOUDIS, S. (2006) Thermal comfort in outdoor urban spaces: analysis across different European countries. *Building and Environment,* 41**,** 1455-1470.
SPAGNOLO, J. & DE DEAR, R. (2003) A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment,* 38**,** 721-738.
UCHIDA, M., MOCHIDA, A., SASAKI, K. & TONOUCHI, T. (2009) Field measurements on turbulent flowfield and thermal environmet in and around biotope with pond and green space. *The seventh International Conference on Ubrna Climate.* Yokohama, Japan.