304: Wind for Comfort in High Density Cities

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Abstract

In tropical and sub-tropical cities where summer is hot and humid, the usage of outdoor spaces is often hindered due to thermal discomfort. In order to improve the thermal condition of the outdoor environment and to make it a delightful place for people to use and enjoy; better provision of wind is thought to be a viable means. This paper presents some of the results of a large-scale outdoor thermal comfort study in Hong Kong which comprises onsite surveys and longitudinal experiments. The preliminary results of the study seem to suggest that under the hot-humid summer climate, with proper sun shading, a wind speed of around 1.5 – 2.5 m/s is needed for the thermal comfort of people.

Keywords: Wind, Thermal Comfort, Hot-Humid Climate, High Density

1. Introduction

Outdoor microclimatic conditions have profound influences on the comfort sensation of people and therefore are important factors to be considered in the design of urban outdoor spaces. In tropical and sub-tropical cities where summer is hot and humid, the usage of outdoor spaces is often hindered due to thermal discomfort. This not just results in the under-use of spaces but the undesirable outdoor environment also overshadows the vivid quality of urban life. For the pleasantness and well-being of urban dwellers, the provision of a thermally desirable outdoor environment is essential. Nevertheless, this represents a great challenge in many densely built Asia cities, especially in the hot-humid summer days.

Prior research concerning indoor environment has shown that the provision of air flow can effectively improve people's thermal comfort [1, 2]. Khedari et al. have conducted an experiment to examine the effect of air flow on people's thermal sensation. Based on the findings, they developed a ventilation comfort chart which shows the inter-relationship between the speed of air flow, relative humidity and people's neutral temperature. According to the ventilation chart, for a typical sub-tropical humid summer day with a relative humidity of 80%, an increase of air speed from 0.5 to 1.5 m/s can raise the neutral air temperature from about 28.5 to 31 ^{o}C [3]. The results have been adopted in a study concerning the comfort temperature for naturally ventilated buildings in Hong Kong; and it has been suggested that indoor natural ventilation to an air speed of about 1.0-1.5 m/s would likely to satisfy the thermal comfort requirement of 80% of occupants under hot summer period in Hong Kong [4].

For outdoor environment, the effect of wind is more complicated as it is often inter-related with solar exposure. In general, in order to achieve the same level of thermal comfort, an increased intensity of solar exposure will result in a higher comfort wind speed. Tacken has conducted a field experiment to investigate the comfortable wind climate for outdoor urban environment and based on the findings, he produced a table showing the comfort wind speed at different combinations of air temperature and solar exposure. According to the table, at an air temperature of 28^{o}C, an increase of solar exposure from 200 W/m^2 (shaded under trees) to 800 W/m^2 (direct exposure under partial cloudy sky) will lead to an increase of comfort wind speed from about 3.5 to 6.0 m/s [5]. Although in theory, a wind speed of 6 m/s is considerably disturbing due to the effect of wind force.

A review of outdoor thermal comfort studies has showed that at air temperature of about 28^{o}C, the comfort wind speed for a pedestrian in shade could vary from 0 to 3 m/s; the large discrepancy is thought to be caused by the diverse climates and cultures involved in the studies. The highest comfort wind speed was obtained from cold climate regions where people there are acclimatized to cold temperature; and therefore a high wind speed is needed to compensate for the high temperature in order to achieve thermal comfort. In hot and humid sub-tropical regions, under a typical summer day, it is suggested that a wind speed ranging from 1 to 2 m/s is required for achieving thermal comfort of people in shade with short-sleeve T-shirt and trousers (0.6 clo) involving in sedentary activities [6].

All in all, past research has provided significant insights about the effect of wind on people's thermal comfort. Through creating an appropriate wind environment in hot-humid tropical and sub-tropical cities, the summer discomfort can be alleviated and the outdoor urban spaces can become more delightful places for people to use and enjoy. In view of this, the Hong Kong Planning Department has commissioned a large-scale study to investigate the air ventilation potential in urban Hong Kong and to study the wind comfort requirement of Hong Kong people. This paper presents some results of this study with emphasis on the effect of wind with regard to the thermal comfort of people. It includes the findings of an outdoor comfort user survey conducted in Hong Kong covering more than 2700 samples and the results of a longitudinal experiment where the thermal experiences of a group of people were followed over changing climatic conditions. It is hoped that the paper will shed light in the design of high density cities, regarding the provision of air ventilation for thermal comfort, under tropical and subtropical climates.

2. Methodology

Two different approaches, i.e. onsite survey and longitudinal experiment, have been adopted in this study. For the onsite survey, the method can be divided into two parts, namely, micro-meteorological measurement and user questionnaire survey. The former includes measurement of the microclimatic conditions at the immediate surrounding of the survey subjects. The latter consists of questionnaire survey for gathering relevant thermal comfort information, which includes the subjects' thermal evaluation, record of their thermal history, demographic background, and clothing and activities during the interview. The results of the questionnaire survey were eventually correlated with the micro-meteorological data recorded in order to find out the average comfort temperature and wind speed of the sample population. This method of onsite survey has an international standing in the field of thermal comfort study and it has been widely adopted in similar research all over the world [7-12]. Figure 1 shows a photo taken during the onsite survey.

Figure 1: Onsite survey

The onsite survey is aimed to provide an understanding of the statistics estimated thermal sensation of an average person; nevertheless, it is also the objective of the study to investigate how the thermal sensation of subjects changes with changing climatic conditions. In order to address the latter issue, a longitudinal experiment has been conducted. In the longitudinal experiment, the thermal sensations of a group of eight subjects were followed over different environmental conditions and subsequently; their thermal sensations under changing climatic conditions were evaluated. The method was introduced by Givoni and has been used in similar studies before [13]. Figure 2 shows a photo taken during the longitudinal experiment.

Figure 2: Longitudinal experiment

The microclimatic conditions in both onsite survey and longitudinal experiment were measured using a mobile meteorological station as shown in Figure 3. It included sensors for the measurement of air temperature, globe temperature, wind speed, relative humidity and solar radiation. The questionnaires used in the two methods were the same to large extent; they dealt with the subjects' sensation of the microclimatic environment 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 50point scale. The overall comfort was rated on a 4-point scale from -2 (very uncomfortable) to +2 (very comfortable). The neutral point zero has been taken out from the scale; therefore subjects were made to express their overall comfort as either comfortable or uncomfortable.

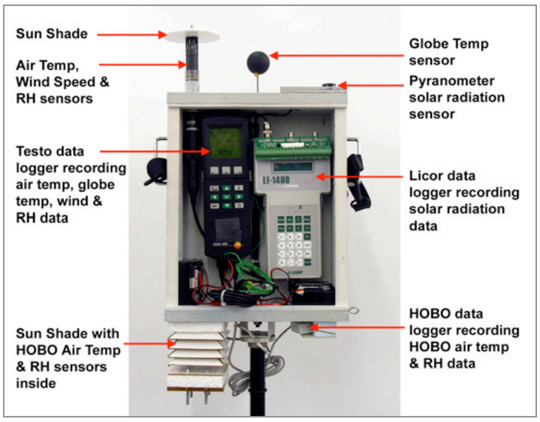

Figure 3: The mobile meteorological station used in the study

3. Results of the Study

3.1 Onsite Survey

The onsite surveys were taken place between October 2006 and August 2007; about 2700 interviews have been conducted in total. They were carried out in many different urban spaces which included public parks, private housing estates, public housing estates, and streets; it is believed that these different environments could capture a wide range of regional climatic conditions, topographic characteristics and building morphology under the urban context of Hong Kong. This paper presents only the data obtained in summer 2007 as the thermal comfort and urban ventilation issues are more critical in the characteristic hot humid summer climate in Hong Kong and in tropical and sub-tropical cities in general.

3.1.1 The Effect of Thermal History

It has been suggested that people's evaluation of thermal comfort towards an environment is affected by their thermal history [14]. In the hot summer period in Hong Kong, indoor spaces are mostly air-conditioned; it is suspected that the prior experience of air conditioning would alter people's thermal evaluation in the comfort survey. Based on a pilot study conducted in summer 2006, there was considerable difference in the thermal sensation votes obtained between subjects who have been to air-conditioned space 5 minutes prior the survey and those who have not. Figure 4 shows the results of an analysis of thermal sensation voting of non air-conditioned and air-conditioned subjects at two levels of wind speed and under similar environmental conditions i.e. average air temperature about 31°C, relative humidity about 70% and solar radiation intensity about 50 W/m^2.

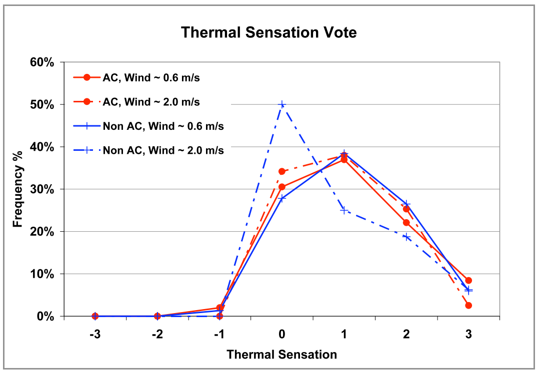

Figure 4: Thermal sensation vote of AC and non AC subjects

Thermal sensation was rated on a scale from -3 (very cold) to +3 (very hot); the central category "0" represents neutral thermal sensation, which is often associated with the feeling of comfortable. The frequency distributions of thermal sensation obtained from air-conditioned subjects at both low and high wind speed scenarios are very close. The peaks are at slightly warm (TS=1) which account for about 38% of all votes; followed by thermally neutral (TS=0) which contributes about 30-35 % of vote. The apparent consistent results obtained at the two wind speed scenarios seems to suggest that an increase of wind speed from 0.6 to 2.0 m/s does not exert noticeable effect on the thermal sensation of air-conditioned subjects.

For non air-conditioned subjects, the frequency distribution of thermal sensation vote at low wind speed is comparable to those obtained from air-conditioned subjects. It has the highest vote at slightly warm (38%) and followed by thermally neutral (28%). However at high wind speed, a remarkable shift of thermal sensation from slightly warm to thermally neutral has been observed. The percentage of thermally neutral vote rises from about 28% to 50% with an increase of wind speed from 0.6 to 2.0 m/s. The result seems to suggest that non air-conditioned subjects are more sensitive to the chilling effect of wind flow; and a wind speed of 2 m/s appears to have substantial effect on their thermal sensation.

3.1.2 The Effect of Wind

The foregoing analysis has shed some light on the provision of wind for thermal comfort; based on this premise, a further analysis of the effect of wind has been conducted using the survey data obtained in summer 2007. Figure 5 shows a plot of the percentage of non air-conditioned subjects at neutral thermal sensation (TS=0) across different wind speed categories. In this analysis, non air-conditioned subjects refer to subjects whom have not been in an air-conditioned space within 15 minutes prior the survey.

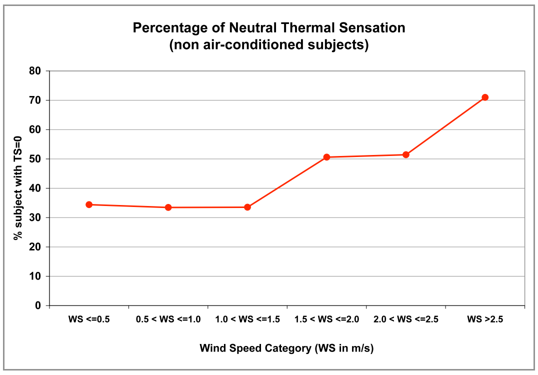

Figure 5: Neutral thermal sensation and wind speed

According to the chart, about 34% of the subjects voted for neutral thermal sensation when the wind speed is lower or equal to 1.5 m/s. However when the wind speed is between 1.5 and 2.5 m/s, the percentage of people at neutral sensation increases sharply to about 51%. A further increase of wind speed to above 2.5 m/s raises the percentage of neutral thermal sensation remarkably to 71%. The results seem to suggest that a wind speed of 1.5 - 2.5 m/s is needed in order for 50% of the subjects to achieve neutral thermal sensation.

3.2 Longitudinal Experiment

Two longitudinal experiments were conducted in the summer of 2006; each survey consisted of 12 experimental sessions, which were carried out in three different periods of the day (i.e. morning, afternoon and evening). Each period comprised four experimental sessions; 8 subjects in 4 pairs were taking turns to sit in different environmental conditions during the four experimental sessions. The environmental conditions employed in the study included: 1) subjects sitting under sun umbrella; 2) subjects sitting within a semi-enclosed wind break; 3) subjects sitting within a semi-enclosed wind break and under sun umbrella; and 4) subjects sitting under direct sun and wind exposure [15]. Total 190 questionnaires were completed in the experiments.

3.2.1 The Effect of Changing Wind Conditions

Figure 6 shows the effect of changing wind conditions on the thermal responses of subjects, as a function of air temperature and with corresponding regression lines. The average wind speed in settings with wind break was about 0.3 m/s; whilst that without wind break was about 1 m/s. In accordance to the regression lines, under the same air temperature, the subjects generally rated the settings with wind break about 0.43 units hotter than in settings without wind break. Based on the data of the wind sensation vote, the subjects generally rated the wind speed as less than appropriate. On average, the wind condition in settings with wind break was rated as too still and that without wind break was rated as slightly still.

The average slope of the thermal responses with changes in the air temperature was 0.23 units/ ^{o}C. The difference between the average thermal responses in the ‘wind break’ and ‘no wind break’ settings was 0.43 units. Therefore, it can be inferred that the effect of increasing wind speed from 0.3 m/s to 1 m/s was equivalent to about 1.9 ^{o}C drop in air temperature. This finding parallels the results of the ventilation and comfort study conducted by Khedari et al. where a temperature difference of about 2 ^{o}C is predicted for an increase of wind speed in this range [3].

By extrapolating the regression lines to the x-axis, the neutral air temperature under the experimental condition can be figured out. According to Figure 4, the neutral air temperature at 0.3 m/s wind speed is about 24.3 ^{o}C; however, when the wind speed is increased to 1 m/s, a higher neutral air temperature of 26.1 ^{o}C can be obtained.

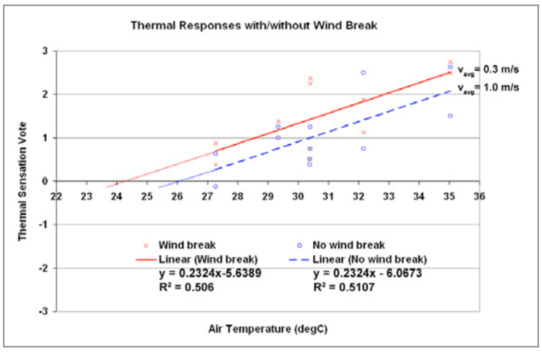

Figure 6: Effects of changing wind conditions on thermal responses

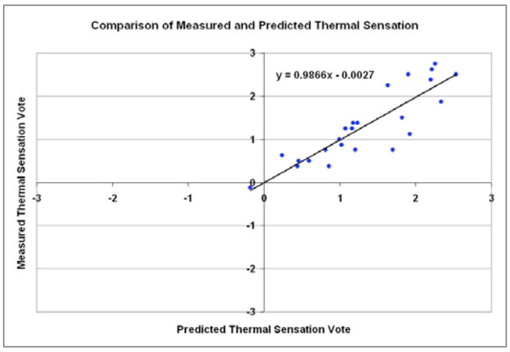

Figure 7: Comparison of the measured and predicted thermal sensation

3.2.2 Predictive Formula for Thermal Sensation

A multi-factor regression analysis has been performed on the collected data. Based on the results, a formula for predicting the subjective thermal sensation vote has been developed. The formula is a function of air temperature, wind speed, solar radiation intensity and absolute humidity; the resulting formula is as follows:

$$TS = 0.1895 \times Ta - 0.7754 \times WS + 0.0028 \times SR + 0.1953 \times H - 8.23$$

TS is the predicted thermal sensation vote on a 7-point scale ranging from -3 (too cold) to +3 (too hot) with the thermally neutral sensation point at 0. Ta is the dry bulb air temperature in degree Celsius; WS is the wind speed in m/s; SR is the solar radiation intensity in W/m^2; and H is the absolute humidity in g/kg air.

Figure 7 shows the correlation between the thermal responses given by the subjects and those predicted by the formula. According to the figure, the regression line is almost diagonal and the correlation coefficient between the measured and the predicted data is 0.87, which is very high. This suggested that the predictive formula performed well in estimating the thermal responses of subjects. However, it should be stressed that the formula was developed based on a very small number of subjects; therefore, it should be considered only as a rough indication of the subjective thermal sensation and may not be generalized to a larger population.

According to the formula, air temperature, solar radiation and absolute humidity have positive relationships with thermal sensation; thus, increasing the quantities of these variables will result in higher thermal sensation vote. Conversely, wind speed has a negative relationship with thermal sensation; therefore, increasing wind speed will lower the thermal sensation vote.

The formula provides a means for estimating the wind speed required to produce neutral thermal sensation in different environmental conditions. As an illustration, in a typical summer day in Hong Kong where air temperature is around 28 ^{o}C and relative humidity 80%; a person with light summer clothing sitting under shade will require a wind speed of 1.8 m/s in order to obtain neutral thermal sensation.

4. Conclusion

This paper presents some findings of a large-scale outdoor thermal comfort study in Hong Kong. The results of both onsite survey and longitudinal experiment seem to suggest that under the hot-humid summer climate, with proper sun shading, a wind speed of around 1.5 – 2.5 m/s is needed for the thermal comfort of people.

The authors wish to share this knowledge we obtained from Hong Kong with a large audience and hope it would help the provision of better outdoor spaces in high density cities in tropical and subtropical regions.

5. Acknowledgements

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