The University of Sydney

Architectural Science Review

Founding Editor: Professor Emeritus H J Cowan

49.2

June 2006 ISSN 0003 8628 www.arch.usyd.edu.au

ARCHITECTURAL SCIENCE REVIEW

Volume 49, Number 2, June 2006

Contents

Keywords: Comfort Temperature; Hong Kong; Natural ventilation,Ventilated buildings

Architectural Science Review
Volume 49.2, pp 179-182
www.arch.usyd.edu.au/asr

Comfort Temperatures for Naturally Ventilated Buildings in Hong Kong

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Received 27 April 2005; accepted 7 November 2005

The subtropical climate of Hong Kong has resulted in a significant amount of energy use for comfort cooling in summer. The situation is getting even worse because of the widespread use of household air-conditioners in high-rise residential buildings in the last two decades. To improve the situation, it is believed that thermal comfort has to be made an important agenda in building design. This paper discusses the adaptive model in thermal comfort, which has been included in the new revision of ASHRAE Standard 55-2004. Furthermore, it demonstrates the development of a comfort temperature chart for naturally ventilated buildings in Hong Kong. Based on the findings of this study, indoor natural ventilation to airspeed of about 1.0 – 1.5 m/s would likely satisfy the thermal comfort requirements of 80% of occupants during the hot summer period in Hong Kong.

Introduction

Hong Kong is the most densely populated city in the world. Our cityscape is determined by the high-rise building blocks which are built very closely together with limited space in-between. The compact high-rise enclosures require an enormous amount of energy to nurture, and among all kind of energy end-uses, space cooling is the single largest consuming item.[1 2] Energy use for space conditioning in commercial sector remained at about 50% of total energy consumption of the sector in the last twenty years, whereas cooling energy used in residential sector climbed steadily from about one-tenth of total energy consumption of the sector in 1984 to about a quarter in 2001.[3] The excessive growth of energy use in residential sector was no doubt resulted from the widespread of household air-conditioners in the last two decades and the situation should not be overlooked. It is clear that thermal comfort has to be made an agenda in building design in Hong Kong, especially for high-rise residential buildings.

As thermal comfort is concerned, *ASHRAE Standard 55-92: Thermal Environmental Conditions for Human Occupancy* is the most frequently cited guidelines in building industries around the world. According to Brager, the standard was originally limited to HVAC operation in buildings with full climatic controls. However, in the absence of any credible alternative, it is applied universally across all building types, climates and populations.[4] Nevertheless, evidences from field-studies of thermal comfort all over the world cast doubt upon the application of the standard to variable environment, and there is a growing controversy as to the influence of human adaptation in our understanding of environmental perception.[5]

The adaptive hypothesis, according to de Dear, predicts that contextual factors and past thermal history modify building occupants' thermal expectations and preferences.[6] As to examine the adaptive hypothesis and its implications for Standard 55-92, an ASHRAE research project RP-884 on adaptive models of thermal comfort was established. The principal objective of RP-884 was to develop a variable temperature standard based on adaptive approach, which ultimately became the framework of the latest revision to Standard 55. The project assembled a quality-controlled database that contains approximately 21,000 sets of raw thermal comfort data from 160 buildings around the world, these buildings include naturally ventilated, mechanically controlled and mixed-mode operation. As to facilitate the use of these thermal comfort data for interested researchers, the entire database has been put in the public domain and is readily available on the World Wide Web.[7]

Based on this comprehensive database, Brager and de Dear, the principal investigators of project RP-884, have developed an adaptive model of thermal comfort and preference for naturally ventilated buildings.[4] Figure 1 shows the proposed comfort temperature standard for buildings with natural ventilation. The chart is the regressions of indoor operative temperature based on mean outdoor air temperature. To use this standard, engineers simply calculate the average of the mean minimum and maximum air temperatures for a given month, and then use the chart to determine the acceptable range of indoor operative temperatures.

Adhering to the aforementioned procedure with known outdoor temperature data, a comfort temperature chart, especially for Hong Kong, could be developed. Figure 2 shows the comfort temperature chart developed. It can be seen from the chart that the comfort temperature of Hong Kong in summer would be up to about 30°C, whereas the lower temperature limit in winter would be about 20°C. Based on this comfort temperature range, one would predict that people generally feel comfortable in summer whereas too cold in winter. However, this prediction contradicts to our daily experience that people would generally find the indoor too hot in summer whereas acceptable in winter. The discrepancy

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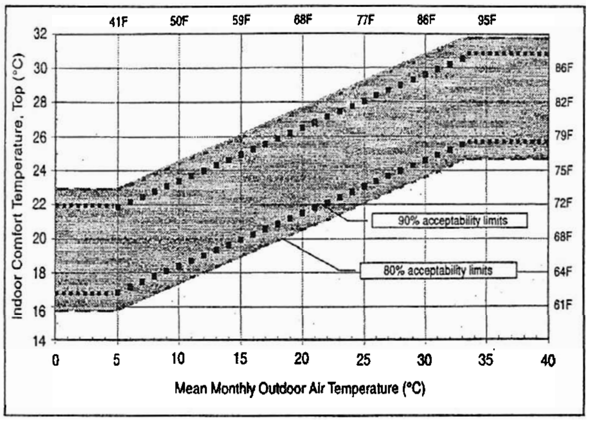

Figure 1: Adaptive model for naturally ventilated buildings. The chart shows the relationship between ideal indoor temperature and outdoor temperature, accounts for all variations, for example, airspeed, clothing, and metabolism measured in the field. ASHRAE Journal, October, 2000. © American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., www.ashrae.org.

between the prediction and daily experience leads to a hypothesis that some of the comfort parameters, such as clothing insulation, metabolic rate, airspeed, and relative humidity, which were incorporated in the adaptive model may not appropriately reflect the context of Hong Kong. In order to use the adaptive model in Hong Kong, adjustments of comfort parameters have to be addressed. This paper demonstrates the development of a comfort temperature chart for naturally ventilated buildings in Hong Kong, which was built on the framework of Brager and de Dear's adaptive model and raw data of selected field survey in RP-884 database, supplemented with desktop literature survey of local studies.

Methodology

Data Selection

In view of the characteristic hot and humid climate of Hong Kong, thermal comfort studies, which conducted in naturally ventilated buildings in summer period, were selected from RP-884 database for this analysis. There are over 7000 field observations from twenty-seven buildings that fulfilled the requirements. These buildings were comprised of thirteen locations including: Thailand, Singapore, Indonesia, Athens, Australian cities Brisbane and Melbourne, UK cities Merseyside and Oxford, Pakistani cities Multan, Peshawar, Quettar and Saidu, and finally US city San Francisco. The mean outdoor temperature of all the selected samples is 23.8 °C with standard deviation ±5.2 °C, which are, indeed, very close to our meteorological record in 2002 [8] with mean annual outdoor temperature about 24.3 °C and standard deviation ±5.0 °C.

Statistical Analysis

The method of statistical analysis was generally based on Brager and de Dear's adaptive model as described thoroughly in ASHRAE RP-884 Final Report [9] with some modifications to suit our later application. In order to reduce the individual influence in the adaptive model, a particular building's observations were binning into half-degree (°C) increments, and analysis working with the bins' mean response, instead of individual subjects. Neutral temperature, the ambient temperature found by statistical analysis to most frequently coincide with the "comfortable" rating in a thermal comfort study, was calculated by fitting a linear regression model between thermal sensations and average indoor air temperature. The neutral temperature is the solution of the linear equation for a mean thermal sensation value of zero, i.e. neutral. The range of index values corresponding with 80% "acceptable" thermal sensations is the distance between solutions of linear equation corresponding with thermal sensations of –0.85 (close to 'slightly cool') to +0.85 (close to 'slightly warm').

Results of Analysis

The Adaptative Model

According to statistical analysis, the neutral indoor air temperatures of all the selected buildings were calculated and were shown in Table 1. The results of RP-884 revealed that indoor neutrality in naturally ventilated buildings, in certain extent, depends on outdoor temperature. Analysis in RP-884 shown that the linear correlation between indoor operative temperature and mean outdoor effective temperature is about 0.65.[6]

Based on the neutral temperatures in table 1 and the corresponding arithmetic average of daily minimum and maximum outdoor air temperature provided by RP-884 database, a linear regression model between indoor neutral air temperature and average outdoor air temperature can be constructed. Figure 3 shows the regression model developed. As can be seen from the figure, there is a reasonably strong correlation for this relationship, with correlation coefficient of about 0.72. Furthermore, the slope of the model suggested that indoor neutral air temperature would

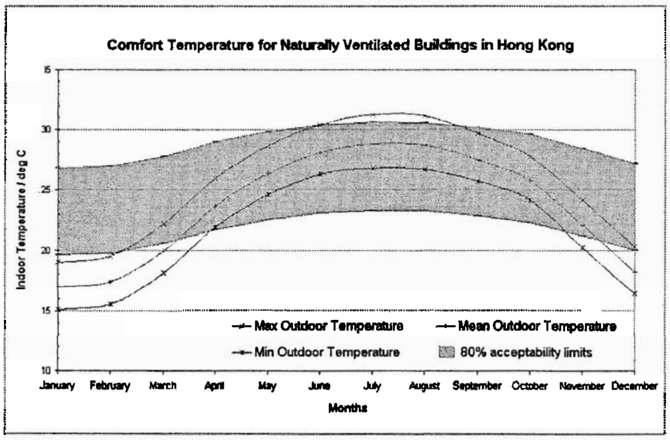

Figure 2: Comfort temperature range for naturally ventilated buildings in Hong Kong, purely based on Brager and de Dear's adaptive model and meteorological data of the years 1997-2003 from Hong Kong Observatory.

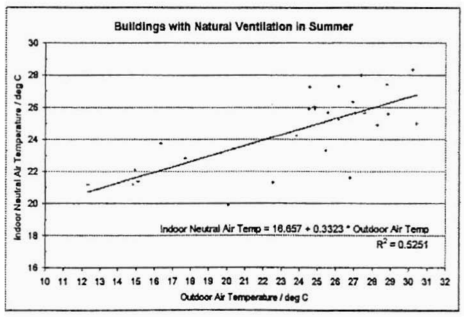

Figure 3: Linear regression model showing the correlation between indoor neutral air temperature and average outdoor air temperature

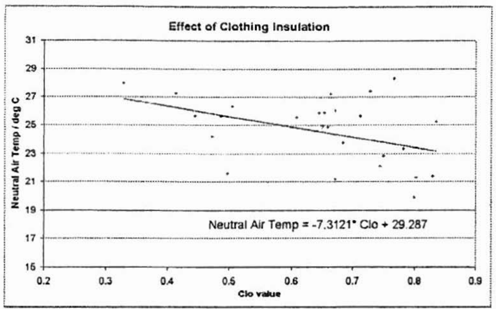

Figure 4: Effect of clothing + chair insulation on indoor neutral air temperature.

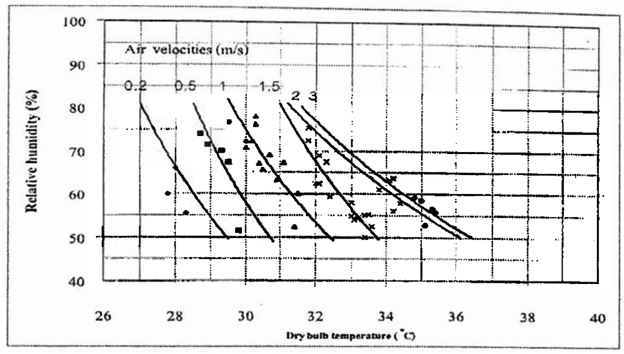

Figure 5: Reprinted from Energy and Buildings, Vol. 32, Khedari et al, Thailand ventilation comfort chart, pp. 245-249, Copyright 2000, with permission from Elsevier.

change by one degree Celsius for about three degree Celsius change in average outdoor air temperature. In comparison of the general forms, our regression model was indeed quite close to Brager's model, except that our model built on air temperature, whereas her model built on operative temperature. Operative temperature takes into account both air temperature and mean radiant temperature and can be assumed to be within ±1°C from air temperature.

Model of this study: $T_i = 16.7 + 0.33 * T_o$ (1)

Model of Brager's study: $T_{op} = 17.7 + 0.31 * T_o$ (2)

T_i: Indoor neutral air temperature (°C)

T_{op}: Indoor neutral operative temperature (°C)

T_o: Average outdoor air temperature (°C)

Adjustment of Clothing Insulation

The first adjustment made was concerned with clothing insulation. As mention earlier in the paper that all the selected field studies were conducted in summer, the mean clothing + chair insulation recorded was about 0.66 and 0.73 clo units at 25°C and 20°C average outdoor air temperature respectively. Chan has conducted a large-scale survey of thermal comfort in Hong Kong [10], based on his findings, the mean clothing + chair insulation was 0.73 and 1.01 clo units respectively in summer (July to September) and winter (December to March). The discrepancy was addressed by adding a correction coefficient to our adaptive model. Figure 4 is a linear regression model between indoor neutral air temperature and clothing + chair insulation. The model suggested that indoor neutral air temperature would change by one degree Celsius for about 0.14 clo units change in mean clothing + chair insulation. Therefore, a correction coefficient of about -0.5 degree Celsius was made in summer and –2.0 degree Celsius in winter. Method of interpolation was used for months in-between.

Adjustment of Metabolic Rate

Mean metabolic rates of the selected samples was about 1.2 met units regardless of indoor temperature, ranging within a fairly tight cluster of 1.1 to 1.4 met units. According to Chan's field survey in Hong Kong, the mean metabolic rate was about 70.6 W/m^2 (about 1.2 met units), which was very close to the samples, therefore, no adjustment was made with respect to metabolic rate.

Adjustment of Airspeed

Worldwide thermal comfort research has confirmed the influence of airspeed on human comfort perception.[11,12] Khedari has conducted an experiment to quantitatively correlate the effect of airspeed with neutral air temperature in Thailand [13]. Based on his finding, Khedari developed a ventilation comfort chart, which shows the inter-relationship between neutral air temperature, relative humidity, and airspeed. Figure 5 shows his chart, which suggested that at constant relative humidity, neutral temperature increases with air velocity. In our adaptive model, mean indoor airspeed of the selected samples was about 0.28 m/s with standard deviation of about ±0.14. Under this airspeed, the indoor

Table 1: Indoor neutral air temperatures of selected buildings.

Buildings	Outdoor Avg. Temp (deg C)	Neutral Air Temp (deg C)	Buildings	Outdoor Avg. Temp (deg C)	Neutral Air Temp (deg C)
Thai_3	28.3	24.9	Indonesia_4	27.6	25.7
Thai_4	28.9	25.6	Melbourne Aust_1	20.1	19.9
Thai_5	30.4	25.0	Melbourne Aust_2	22.5	21.3
Singapore_2	27.4	28.0	Merseyside UK_3	12.3	21.2
Athens_1	25.6	25.7	Multan Pak_2	28.8	27.4
Athens_2	26.1	27.3	Oxford_1	14.9	22.1
Athens_3	23.8	24.2	Oxford_2	15.1	21.4
Athens_4	26.8	21.6	Oxford_3	14.8	21.2
Athens_5	27.1	25.7	Peshawar Pak_3	30.2	28.4
Athens_6	26.9	26.3	Quettar Pak_4	25.4	23.3
Brisbane Aust_1	24.8	25.9	Saidu Pak_5	26.2	25.2
Brisbane Aust_2	24.5	25.9	San Francisco_1	16.3	23.8
Brisbane Aust_3	24.6	27.3	San Francisco_6	17.7	22.8
Brisbane Aust_4	24.8	26.0			

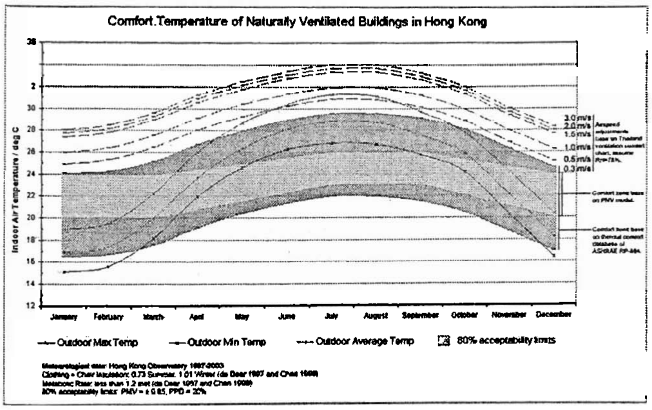

Figure 6: Comfort temperature chart for naturally ventilated buildings in Hong Kong.

maximum air temperature with 80% acceptability in naturally ventilated buildings was about 29.5°C in hot summer. It is expected that the indoor neutral temperature can be raised by providing better ventilation, i.e. higher airspeed. The effect of airspeed is accounted for in our adaptive model by reproducing the air velocity- lines in figure 5 on our comfort temperature chart. Figure 6 is a comfort temperature chart for naturally ventilated buildings in Hong Kong, based on the aforementioned analysis and all adjustments.

Conclusion

Based on the comfort temperature chart (Figure 6), under an airspeed of about 0.3m/s, one would expected that people will find the indoor too hot in summer whereas acceptable in winter. However, when airspeed is increased to about 1 m/s, the upper comfort temperature limit increased by about one degree Celsius and the comfort range just cover the maximum outdoor air temperature in hot summer. When airspeed is increased to about 1.5 m/s, the upper comfort temperature limit further moved up 1.5 degrees to about 33.5 degree Celsius and the predicted comfort range far above the maximum outdoor air temperature. The result of this study suggested that indoor natural ventilation to airspeed of about 1.0 – 1.5 m/s would likely satisfy the thermal comfort requirement of 80% of occupants under hot summer period in Hong Kong.

The adaptive model developed in this study was based on selected observations from ASHRAE project RP-884 database. Although the samples include twenty-seven buildings from thirteen locations, only a limited number of them have the characteristic hot and humid climate like Hong Kong. Furthermore, the model was built on a number of presumed values of comfort parameters, such as clothing insulation, metabolism, airspeed, and relative humidity. Therefore, it has its own limitations. The adaptive model developed in this study is all we could obtain on the basis of current available knowledge in the area. To improve the accuracy of this model, further research in thermal comfort in naturally ventilated buildings in Hong Kong is essential.

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