A STUDY OF TEMPERATE CLIMATE FOR COMFORT TEMPERATURE PREDICTIONS IN NATURAL VENTILATION BUILDINGS USING ASHRAE RP-884 DATABASE

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**FACULTY OF ENGINEERING
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DECLARATION

I hereby declare that the material in this thesis is my own except for the quotations, excepts, equations, summaries and references, which have been duly acknowledged.

06TH August 2018

Tay Lee Yong
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CERTIFICATION

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ABSTRACT

Many studies addressed the effect of climate on thermal comfort by referring either to the developed climate world map designed by Kottek et al or by Peel et al method. However, they ignored the fact that each method may provide different results. Additionally no consideration was made in their studies by addressing the effect of climate subtypes on thermal comfort, the variation of climate over years on thermal comfort, and the variation of the monthly neutral temperatures over years due to climate variation. Hence, this research addressed the effect of the Köppen-Geiger climate classification systems on thermal comfort of various locations subjected to climate type C. The ASHRAE RP-884 database was used in the investigation. At the initial stage, Kottek and Peel climatic world maps of Köppen-Geiger, and the New LocClim 1.10 software were used for the identification of main climate types. Ten survey sites subjected to climate type C were identified. In the next stage, three locations were further selected for the identification of main and subtypes climate over a period of 35 years (1980-2014). The Kottek and Peel versions of Köppen-Geiger climate classification were used. A comparison was made by considering short-versus long-term climate types. In the final stage, the dominant long-term, the average long-term, and the short-term neutral temperatures were predicted and analysed according to main and sub-climate types. The analysed results revealed that shifts in climate types did not necessarily affect the predicted indoor neutral temperatures. It was also observed that the neutral temperature, when determined using the thermal comfort survey conducted in a year or in a few months, was also subjected to variation. The Köppen-Geiger approach seems not to be an appropriate method for predicting and monitoring the effect of climate variation and change on humans' thermal comfort. It cannot be used to investigate the impact of relative humidity on thermal comfort.

ABSTRAK

KAJIAN IKLIM SEDERHANA UNTUK RAMALAN SUHU KESELESAAN DALAM BANGUNAN PENGUDARAAN SEMULA JADI MENGGUNAKAN PANGKALAN DATA ASHRAE RP-884

Banyak kajian menekankan kesan iklim terhadap keselesaan terma dengan merujukkan kaedah peta dunia iklim yang direka oleh Kottek et al. atau Peel et al. Namun demikian, mereka mengabaikan hakikat bahawa setiap kaedah boleh membawakan hasil yang berbeza. Di samping itu, tiada pertimbangan yang dibuat dalam kajian mereka dengan menekankan kesan sub jenis iklim terhadap keselesaan terma, variasi iklim selama bertahun-tahun dalam keselesaan haba, dan variasi suhu neutral bulanan selama bertahun-tahun disebabkan oleh perubahan iklim. Oleh itu, kajian ini membincangkan tentang kesan klasifikasi iklim Köppen-Geiger terhadap keselesaan terma di pelbagai lokasi yang tertakluk kepada jenis iklim C. Pangkalan data ASHRAE RP-884 telah digunakan dalam kajian ini. Pada peringkat awal, peta cuaca dunia Köppen-Geiger Kottek dan Peel, dan juga perisian New LocClim 1.10 telah digunakan untuk pengenalpastian jenis iklim utama. Sepuluh tapak tinjauan yang tertakluk kepada jenis iklim C telah dikenalpasti. Di peringkat seterusnya, tiga lokasi telah dipilih untuk mengenal pasti iklim utama dan sub jenis iklim dalam tempoh 35 tahun (1980-2014). Kottek dan Peel versi klasifikasi Köppen-Geiger telah digunakan. Perbandingan telah dibuat di antara jenis iklim jangka pendek dan jenis iklim jangka panjang. Pada peringkat akhir, suhu neutral berdasarkan jangka panjang yang dominan, purata jangka panjang, dan jangka pendek telah diramalkan dan dianalisis mengikut jenis utama dan sub iklim. Hasil analisa menunjukkan bahawa perubahan dalam jenis iklim tidak semestinya membawa effek terhadap suhu neutral dalaman yang diramalkan. Ia juga diperhatikan bahawa suhu neutral juga tertakluk kepada variasi apabila menggunakan tinjauan keselesaan terma yang dijalankan dalam setahun atau dalam beberapa bulan. Ini telah menunjukkan kaedah Köppen-Geiger bukan satu kaedah yang sesuai untuk meramal dan memantau kesan variasi iklim dan perubahan terhadap keselesaan terma manusia. Ia tidak boleh digunakan untuk menyiasat kesan kelembapan relatif terhadap keselesaan terma.

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LIST OF ABBREVIATIONS

Acc.	Accumulation
Ann.	Annual
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Avg.	Average
Climate Type A	Tropical Climates
Climate Type B	Arid Climates
Climate Type C	Warm Temperate Climates
Climate Type D	Snow Climates
Climate Type E	Polar Climates
FAO	Food and Agriculture Organization
HVAC	Heat-Ventilation and Air Conditioning
Ltm.	Long-term
Max	Maximum
Min	Minimum
Mthly.	Monthly
NV	Natural Ventilated
P_{ann}	Accumulated Annual Monthly Totals of Precipitation (Summation of 12 monthly totals of precipitation values from January to December)
P_{min}	Monthly totals of precipitation of the driest month
P_{max}	Monthly totals of precipitation of the wettest month
Pr.	Precipitation
SCATs	European Smart Controls and Thermal Comfort
SD	Standard Deviation
T_{ann}	Annual Mean Air Temperatures (average of 12 monthly temperature values from January to December)
$T_{neutral}$	Predicted Neutral Temperature
T_{max}	Monthly Mean Air Temperature of the Warmest Month
T_{min}	Monthly Mean Air Temperature of the Coldest Month
Temp.	Temperature

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LIST OF DEFINITIONS

Kottek's map	refers to the Kottek world map of the Köppen-Geiger climate system as stated in the publication (Kottek *et al.*, 2006).
Kottek's method	refers to the calculation procedure as stated in the publication (Kottek *et al.*, 2006).
Liverpool	refers to three places in the UK, namely; Liverpool, St. Helens, and Chester. This was made from chapter 5 to 7.
Main climate type	refers to A, B, C, D and E climates of the Köppen-Geiger climate system as in their publication (Kottek *et al.*, 2006; Peel *et al.*, 2007).
Neutral temperature	refers to the optimum comfort temperature (ASHRAE 55, 2013).
Peel's map	refers to the Peel world map of the Köppen-Geiger climate system as stated in reference (Peel *et al.*, 2007).
Peel's method	refers to the calculation procedure as in their publication (Peel *et al.*, 2007).
San Francisco bay	refers to San Francisco and Berkeley locations only.
Subtype	refers to the secondary and tertiary of main climate types, for example Csb.
Survey Year	refers to the year where thermal comfort study was conducted as stated in ASHRAE RP-884.

CHAPTER 1

INTRODUCTION

1.1. General

Buildings provide a comfortable living environment for their occupants (Roulet, 2001). This includes, among others, thermal, visual and acoustic comfort, as well as indoor air quality. It is widely accepted fact that buildings are not isolated but are generally placed in an urban context, thus open to influences by urban heat island and global warming. Urban warming has serious consequences on the energy, environmental, and social balance of cities, as well as on human comfort and health (Santamouris, 2014). The associated effects of urban heat island and global warming have increased the near-surface temperature in cities (Alves, Duarte and Gonçalves, 2016).

Human health acts as an important factor in determining the quality of life of an occupant. From late 1980s until 1990s, the concept of health (for example, health in terms of indoor air quality, thermal comfort, lights quality, and acoustics), from the stance of World Health Organisation (WHO), turned significant as identifiers of the "healthy building" concept (Bluyssen, 2010).

A healthy building means that the building is free of hazardous materials and is capable of fostering the health and comfort of its occupants during its entire life cycle, along with supporting its occupants' social needs and enhancing their productivity (COM, 2007). A healthy building recognises that human health needs and to some extent, comfort needs, are priorities. Additionally, a healthy building should be ready for the future. It should also be adaptable to "new drivers" such as climate change, the observed changes in the types of end-users' wishes and demands, and others (Iacobucci, 2001).

A healthy building also depends on building thermal performance which in turn affects building energy performance. Building energy performance depends not only on building design but also on local climatic conditions, including ambient temperature, humidity, solar radiation, and wind (Roulet, 2001). A building that is well-adapted to the climate protects its inhabitants against the extreme conditions observed outdoors without creating uncomfortable internal conditions. Changes in the local climate may also alter building energy consumption (Wang, Chen and Ren, 2011). For example, a warming climate reduces the heating energy requirement in relatively cold climates (Ward, 2008). However, a warming climate may increase the cooling energy requirement of buildings during a warm season (Papakostas, Mavromatis, and Kyriakis, 2010). The increase in cooling energy consumption may eventually offset or exceed the benefit from the saving of heating energy, especially in subtropical regions (Lam, Wan, Lam, and Wong, 2010).

1.2. Background of Study

Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment (ASHRAE, 2013). Adaptation is an important factor of human thermal comfort in ensuring humans' life and health on Earth. Adaptation can be physiological, psychological, or behavioural. Therefore, a wide range of thermal comfortable conditions and a close relationship with the external climatic environment can be achieved (Yan, Yang, Zheng and Li, 2016). Currently, adaptive thermal comfort models are widely used to evaluate indoor thermal conditions in naturally-ventilated (NV) buildings (Alves, Duarte, Gonçalves, and Tateoka, 2014). Assessing the impacts of climate and determining the adaptation requirements will certainly lead to the development of beneficial and reliable information that can be used to mitigate the impact of climate on human thermal comfort. It has already been reported that humans respond to adaptation mainly through reducing or eliminating the risks of climate change impacts (Alves *et al.*, 2016).

During the years starting from 1995 to 1997, de Dear (1998) collected 22,000 sets of data and developed an adaptive regression model. The model required outdoor air temperature data for the prediction of indoor neutral temperature. This is because any change in outdoor air temperature will affect the indoor thermal comfort conditions according to human adaptation. ASHRAE 55 is a widely recognised thermal comfort standard in predicting comfort temperature. An adaptive thermal comfort model in naturally-ventilated (NV) buildings was introduced in the standard since 2004 (ASHRAE 55, 2003). The adaptive comfort model was developed using the ASHRAE RP-884 database from surveys conducted all over the world (Toe and Kubota, 2013). A regression model for the prediction of comfortable temperatures was proposed. Today, the model is still recognised by the ASHRAE standard and it has been widely used by many investigators in the world.

1.3. Problem Statement

There is no doubt that the climate of the Earth keeps changing from time to time. Although there has been obvious progress in monitoring and understanding climate change, there remain many scientific, technical, and institutional impediments to precisely planning for, adapting to, and mitigating the effects of climate change (Karl and Trenberth, 2003).

In this regard, the Köppen-Geiger climate classification system is the most widely used and referred model in the world in various disciplines (Kottek *et al.*, 2006). This is not an exception in thermal comfort studies. In recent years, several authors had considered the Köppen-Geiger climate classification in their articles just to cite a few references (Yang and Matzarakis, 2015; Croitoru, Nastase, Crutescu and Badescu, 2016; Toe and Kubota, 2013; Kabre, 2018; Nobatek, 2016; Mishra and Ramgopal, 2013; 2015).

Most thermal comfort researchers in their investigations referred to the developed climate world map of Köppen-Geiger designed by Kottek *et al.*, (2006). In fact, many researchers ignore the updated version which was developed one year later by Peel *et al.*, (2007). Further, little is known about the implications of using Peel's *et al.*, (2007) climate world map to predict thermal comfort or address the impact of climate types on neutral temperatures.

Mishra and Ramgopal (2013) investigated the reliability of adaptive comfort equations taken from studies on various climate types. However, they concluded that except for main climate type A, other climate types have wide ranges of neutral temperatures. Unfortunately, their study only considered Kottek's *et al.*, (2006) climate world map. The map was developed according to the Köppen-Geiger procedure. The authors not only ignored the updated version of Kottek's *et al.*, (2006) map which was developed by Peel *et al.*, (2007), they also only considered the main climate types and omitted the climate subtypes. In fact, Peel *et al.*, (2007) made some modifications to the Köppen-Geiger classification method. Additionally, the usage of any climatic map is very restrictive as it is limited to the selected period of time. The climate of a location is also subjected to yearly variation. Further, the Kottek and Peel maps were only developed using the average air temperature and precipitation data over a selected period of time. An average long-term climate type may not necessarily be the dominant climate type. In fact, it does not necessary reflect the yearly climate type when the thermal comfort survey was conducted. Therefore, a further investigation in this direction is important for the generalisation of conclusions made by some authors.

In another study, Toe and Kubota (2013) classified the climate types of several places into three climate groups according to survey location and season. The selected climate types are hot-humid, hot-dry, and moderate. The main purpose of their study was to develop an adaptive model equation for the hot-humid climate. In their study, the investigators selected Peel's *et al.*, (2007) method for their research work. However, the authors made some assumptions in categorising the locations under the hot-humid classification based on the description of climate types included in the Köppen-Geiger classification. For instance, they assumed that the climate of locations subjected to climate type A and Cfa during summer as hot-humid climate. Such classification has yet to be validated. It is probably important to report that both studies explored at least the ASHRAE RP-884 database in their research.

Natural ventilation has proven to be an energy-efficient alternative in reducing the running costs of buildings, achieving thermal comfort, as well as maintaining a healthy indoor environment. However, owing to the unpredictable

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