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Indoor thermal comfort predictions: Selected issues and trends

Harimi Djamila

Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia

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ABSTRACT

Thermal comfort is a complex topic and the methods studied so far are only approximate. Many investigators are likely to face some of the issues addressed in this article. The focus of the review is on selected issues and trends relevant to thermal comfort. Meta-analysis was performed using the ASHRAE RPA-884 database. The aim is to address some of the methodological issues of preliminary data analysis and predictions of comfort temperatures. An examination of how to assess the age factor for thermal comfort consideration in the ASHRAE database was also conducted by using an explicit transparent methodology. A new procedure was developed for predicting and analysing comfort temperature. The suggested procedure goes beyond the obvious need for more research studies to underscore deficiencies in data collection, which will lead to better data analysis. Editors might use the results and recommendations from this investigation before publishing original research on thermal comfort.

1. Introduction

Energy demand is expected to increase in the near future due to global warming, the urban heat island effect, and other factors. Many studies have been carried out globally in the field of thermal comfort to optimize energy usage. Despite the worldwide energy crisis, a considerable amount of energy is consumed every year due to thermal comfort considerations. In parallel, an exponentially growing number of research studies on thermal comfort have been seen in the last few years [1]. Unfortunately, little is available about the effect of the adopted methodology on the prediction of comfort temperatures from field studies. A large-scale field study is most likely to be favoured by reviewers because of the sample size. However, the prediction of comfort temperature is not solely subject to the sample size. It is also essential to consider the patterns of data collection in the prediction of comfort temperatures and to take into account other factors. According to Wasserman [2],

> *Results from observational studies start to become believable when: (i) the results are replicated in many studies; (ii) each of the studies controlled for possible confounding variables, (iii) there is a plausible scientific explanation for the existence of a causal relationship.*

Field studies have little control over thermal comfort parameters and the characteristics of participants. Each of the parameters affecting subjects' thermal perceptions has the potential to unintentionally affect the results [3]. Consequently, meta-analyses that combine the findings of several studies have the ability to detect obvious patterns and produce interesting generalized results when possible. Once again, the results of a meta-analysis reflect the results obtained from individual studies. It is likely that if the individual studies are poorly designed, the results of a meta-analysis may not be useful [3]. The sample size, duration, time, location, and indoor and outdoor climates are some of the factors affecting thermal comfort results. Yet, comparisons of conclusions drawn by investigators are vital in observational research studies.

Currently, there is no specific data collection procedure for predicting neutral temperature. Thermal comfort studies are afflicted with uncertainty. If the dependent or independent variable turns out to be unreliable, further inference is distorted.

This article endeavours to address the associated thermal comfort methodological problems and their effect on the analysis and prediction of comfort temperature from various studies, thus filling part of the research methodology gap. The first objective is to identify quantitatively the effect of thermal comfort parameters on preliminary data analysis. This is done by exploring the effect of sampling design and descriptive statistics on prediction of comfort temperature. The second objective is to develop a clear methodology for predicting the optimum comfort temperature from a single study and combined studies. In the present study, the ASHRAE RP-884 database was selected [56]. This is the only openly available database for all researchers.

E-mail address: harimi1@yahoo.fr.

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2. Complexity of thermal comfort research studies

When designing a building for human thermal comfort, several factors require careful consideration, such as energy efficiency, the occupants' thermal requirements, climate variations, the occupants' heath, and many others [4]. Human behaviour is an important factor in thermal design of buildings. This is because unoccupied buildings do not require energy but humans do [5].

Unfortunately, it is very difficult to predict human behaviour toward the indoor thermal environment under varied conditions. Humans are continuously responding and adjusting to the indoor thermal environment. Such continuous adjustments enable humans not only to produce the optimum desired outcome under various indoor climates but also to survive under extreme climates. Other factors such as cultural, religious, social, and economic ones also affect humans' thermal perception and thermal comfort. In fact, it was reported that culture, religion, education, and experience tend to mediate our perception of the thermal environment [6]. This renders thermal comfort a complex topic.

The worldwide interest in minimizing energy consumption for thermal comfort and the complexity of the topic have led to the publication of more thermal comfort research studies. Thermal comfort surveys are costly and thus the methodology should be carefully designed and clearly reported.

3. Thermal comfort models

When a theory is developed, it is crucial that it is statistically tested in a research study. This is because humans exhibit variability in their thermal perceptions and behaviours. Thus by testing a theory statistically, we may obtain contradictory results. This may lead to a new discovery. Theories evolve and change over time [7]. Thanks to the works of Fanger and others, thermal comfort has become a discipline [8]. Currently, the predicted mean votes (PMV) and the adaptive models are widely used and recognized, at least in the ASHRAE standard [9].

Fanger initially developed the PMV model of a large number of subjects for use within temperate climate zones [10]. The model has been established as an international standard since the 1980s. It was developed based on the principles of thermal heat balance with the physiology of thermoregulation. An empirical fit of subjects' votes on the ASHRAE seven-point scale was used for the adjustment of the model [11]. The model requires six parameters: air temperature, mean radiant temperature, relative humidity, air movement, clothing insulation, and metabolic rate. The PMV model predicts the comfort temperatures well under a controlled environment, specifically under a cold climate [13]. Mishra et al. [4] stated that having more control over the surrounding environment might increase people's satisfaction toward their indoor thermal environment. This can be achieved, for instance, by providing personalized thermal environments.

In naturally ventilated buildings, behavioural, physiological, and psychological adaptive processes are important factors affecting comfort temperatures [12]. These factors are ignored in the PMV model. Occupants are not static but rather interact with their surroundings through adaptation [13]. The PMV model ignores the variation of subjects' state of mind over time. Subjects' long-term adaptation and changes are not taken into consideration in Fanger model. Occupants are subjected to different adaptation decisions in their daily lives. They may opt for the most awarding choices while considering all restrictions. An interesting quote may provide a better description of the situation [14]:

> *The perception of time involves an awareness of change, and there is no change. One can hardly speak of "behaviour" … it just sits there "doing nothing".*

This statement describes better the concept of the PMV model for predicting comfort temperature, even though the quoted statement is not about thermal comfort. Arens and Zhang conveyed that when the skin temperature is actively decreasing or increasing, the person perceives the thermal environment as much colder or warmer than when the temperature remains the same [15]. This shows, further, that the PMV model is only valid under steady-state conditions.

In 2004, the ASHRAE 55 standard replaced the PMV with the adaptive graph for naturally conditioned spaces only [16]. The adaptive model requires the examination of the data gathered during comfort surveys from field studies [17]. The ASHRAE model was developed based on a statistical analysis of about 21,000 records of indoor climatic observations and subjective assessment of thermal comfort [18]. The model was established mostly by the efforts of de Dear and Brager [19,20]. Upon the endorsement of the adaptive method in the ASHRAE 55-standard, the adaptive method was used pervasively in thermal comfort research studies. In recent years, many studies have developed adaptive thermal comfort models according to climate and location [21–24]. A recent adaptive model was developed in India. The investigators found that their adaptive model is also valid and robust within mixed mode buildings [25]. The adaptive model seems to be the preferred choice when considering energy savings under hot climatic conditions. The situation is probably the opposite under cold climates: the PMV model may help in minimizing energy consumption for heating purposes in cold to very cold climates.

The rapid spread of the adaptive model can probably be traced back to several factors. Firstly, the adaptive equation (not the elaborated theory) is a friendly and easy model compared to the PMV model. It requires outdoor air temperature values only; moreover, the historical monthly outdoor temperatures can be used for the prediction of the comfort range.

Although several investigators supported the adaptive approach concept, it has been reported that the adaptive approach has a tendency to produce varying outcomes from different field studies [10]. In fact, the accuracy of the prediction of comfort temperatures for the adaptive model is tied to the accuracy of the predicted indoor comfort temperatures from various studies. The accuracy of the predicted indoor comfort temperature of a single study relies on the quality of the data recorded during the survey. It is also linked to the approach used for the prediction.

The present study does not intend to argue about the PMV model or the adaptive model, which is beyond the scope of the study. It rather provides insight into the ASHRAE database by analysing and interpreting the data using visualization and other techniques. Data visualization as an observational tool has been recently established as a definite discipline [26]. Visualization techniques have been developed to discover patterns, trends, or sub-problems in several datasets.

4. Methodology

In this investigation, the ASHRAE RP-884 database was selected. A few assumptions and requirements were considered prior to data analysis. The data of responses to longitudinal surveys were assumed independent. This assumption is widely accepted in thermal comfort studies. For instance, in the European Smart Controls and Thermal Comfort (SCATs) project, the investigators assumed that the data were independent even though each respondent reported his or her thermal perception of the indoor environment monthly [27]. The SCATs project forms the basis of the adaptive model for European offices [27]. It has been reported that, in an early study by McIntyre [28], the variability among subjects' thermal comfort votes was found to be close to the variability of votes from one subject [27].

In this investigation, the preliminary requirements for a study to be considered for further analysis in this article are that all the environmental, personal thermal comfort, and subject age parameters should be reported.

The operative temperature is a widely accepted index for prediction