Progress and Future Prospects of Habitat Thermal Comfort Research

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Abstract. This paper is a comprehensive study in the topic of human environment and thermal comfort. Firstly, it introduces the concept of thermal comfort and its key role in human environments, and describes the influence of different factors on thermal comfort; secondly, it discusses the commonly used methods of thermal comfort assessment and the assessment indexes in different hot and humid environments; furthermore, it discusses the technologies and strategies to improve thermal comfort, such as the design of ventilation and air-conditioning systems as well as the green building materials, and so on. This paper intends to give a complete literature review for the study of human environment and thermal comfort, and to provide references and recommendations for future research and practice in related domains.

Keywords: Human settlement environment; Thermal comfort; Assessment methods; Improvement techniques.

1. Introduction

With the growth of science and technology and the rise of living conditions, people have increasing and higher criteria for the building environment. A great thermal and humid atmosphere has a non-negligible impact on improving people's health and promoting job efficiency. Therefore, research on thermal comfort has been significantly stressed by the international academic community.

To address the susceptibility of most long-term thermal discomfort measurements to changes in boundary conditions, Carlucci presented a comfort-independent long-term dissatisfaction rate (LPD) metric, which proved strong predictive performance [1]; Pickup et al. modeled the outdoor mean radiant temperature (OUT_MRT) by introducing the mean radiant temperature (OUT_MRT), expanding the application of the standard effective temperature (SET*) to the outdoors, generating the outdoor mean radiant temperature (OUT_SET*) [2]; Arens et al. conducted data comparison and calibration based on three databases, namely ASHRAE, SCAT, and BCC, and pointed out the inadequacies of the Class A thermal comfort standard [3]; given the limitations of the standard PMV-PPD model in predicting the actual thermal environment, Du et al. developed a logistic regression method based on the China Thermal Comfort Database to estimate the optimum indoor temperature range [4]. Kim et al. proposed a new PMV (nPMV) adaptive model based on adaptive thermal comfort theory, which significantly improved the prediction performance of traditional PMV models [5]; Davoodi et al. developed a new human thermoregulation model (ITB) based on skin surface thermoreceptors, which further improved the accuracy of thermal comfort assessment by predicting the response of living tissue layers [6]. These studies not only highlight the richness and complexity of the thermal comfort sector, but also give significant references and ideas for future research.

The purpose of this study is to explore how to create a built environment that is both comfortable and energy efficient. It begins with an introduction of the relevance of thermal comfort and its key contributing factors, followed by a review of the prevalent assessment methodologies and metrics applicable to varied contexts. In addition, the paper analyzes numerous technologies and tactics to promote thermal comfort, aiming to give a complete literature overview of the topic of thermal comfort research and provide direction for future study and application in the field.

2. Importance and Influence of Thermal Comfort

Thermal comfort is defined in the ASHRAE 55 standard as a psychological state of satisfaction with the thermal environment [7]. Physiologically, it involves the body's regulatory centers processing signals from various receptors in the body; psychologically, thermal comfort is not just a neutral state, but also includes pleasure and relief of discomfort. Thermal comfort has important implications for health, and the study of thermal comfort can, to a certain extent, influence people's productive lives and minimize the detrimental effects of thermal conditions on the human body.

Thermal comfort is affected by a combination of factors, which can be analyzed from three dimensions: environmental factors, individual differences and adaptive theory. First of all, the environment is the primary element that impacts thermal comfort, and they are directly involved in and manage the heat exchange process between the human body and the environment. Huang et al. established the tight connection between indoor airflow environment and human thermal comfort by numerical modeling [8]. Yin et al. performed CFD simulation to find that an air supply angle of 15° upward and 15° to the right provided the highest thermal comfort [9].

At the individual level, in addition to metabolic rate and garment thermal resistance, variables such as age, gender, and economic conditions also have an impact on thermal comfort. A study by Indraganti et al. showed that older persons have lower thermal tolerance, whereas women tend to demonstrate a stronger desire for warmer surroundings, and additionally, low-income groups have higher tolerated temperatures than high-income groups [10].

Adaptation theory emphasizes that people are not recipients of their environment, but active adapters. Such adaptations include behavioral adaptations (e.g., modifying clothing, activity level), physiological adaptations (genetics and habits), and psychological adaptations (expectations and experiences).

In essence, the realization of thermal comfort is a multidimensional balancing process. It demands us to understand not only the impact of objective environmental conditions, but also to consider individual responses, as well as people's ability to adapt to environmental changes.

3. Thermal comfort assessment methods and indicators

Assessment methods are the tools and procedures used to measure and evaluate the thermal environment and human perception, while assessment indicators are the specific values derived from the assessment methods to characterize the quantitative criteria for thermal comfort. Some of the classic methods and indicators are described in detail below.

3.1 Thermal comfort assessment methods

Thermal comfort assessment methods can be categorized into subjective and objective assessment methods according to the investigation method. Subjective assessment methods obtain individual feelings through questionnaires, interviews, or the use of specific scoring systems, e.g., Liu conducted a thermal comfort evaluation of naturally ventilated buildings based on subjective questionnaire survey methods and verified the difference between PMV and AMV under natural ventilation [11]. This method relies on individual subjective feedback, is susceptible to incentives, and the results are more ambiguous, thus it is only ideal for evaluating comfort feelings of individuals in a small area, such as homes, small offices, and so on.

Objective evaluation methods use sensors to measure environmental parameters and human physiological responses. They include the PMV-PPD model, the human thermophysiology model, and the thermal sensation model. The PMV-PPD model is based on Fanger's theory of human heat balance, and evaluates comfort by combining environmental and individual parameters. The model has a good ability to predict comfort in a steady-state air-conditioned environment. However, it was noted that when the environment deviates from the neutral temperature, the accuracy of predicting the rate of dissatisfaction is only 1/3 [12]. In addition, factors such as ethnicity and age have not been considered, therefore the model is only applicable to a wide range of locations such as offices and commercial buildings. Human thermophysiological modeling is a direct evaluation of thermal sensations by measuring human physiological indicators such as skin temperature, heart rate, etc. Stolwijk developed a multi-node physiological model for aerospace applications that divides the human body into six sections, each of which is radially divided into four layers, significantly improving the prediction accuracy [13]. Such models provide an objective means of evaluating thermal comfort in situations where it is required, such as scientific research and medical experiments, through the accurate measurement of physiological metrics. Thermal sensory models, on the other hand, utilize physiological or environmental data to perform objective calculations and simulations based on consideration of the body's perceptual mechanisms. The thermal sensory model (UCB model) developed by Edward et al. is a typical representative of this type of model, which is capable of explaining and predicting the phenomenon that the overall thermal comfort is dominated by one or a few localized discomforts [14]. The UCB model is a typical example of this type of model. The model integrates neurophysiological and psychological mechanisms, and therefore shows a high degree of accuracy in assessing localized comfort such as seats and beds.

Evaluation methods are categorized by model type into steady-state and dynamic heat transfer models. Traditional steady-state methods, such as PMV and PPD models, focus on thermal comfort in a stable environment. Dynamic models, on the other hand, take into account the adaptation of people to changes in the environment over time and are particularly suitable for the assessment of naturally ventilated and non-centralized air-conditioning system buildings. For example, the adaptive comfort model proposed by ASHRAE 55 [7] adjusts the indoor set temperature according to the outdoor temperature, reflecting people's physiological and psychological adaptations to climate change over time, as well as the effects of individual adjustment behaviors. This model is more in line with real life and is suitable for comfort evaluation of naturally ventilated buildings.

3.2 Thermal comfort indicators

3.2.1 PMV-PPD

PMV is a predicted thermal sensation voting value for a given parameter in a given environment given on the ASHRAE Thermal Sensation Rating Scale. Fanger developed an experimental regression equation reflecting the correlation between human heat load and thermal sensation by analyzing thermal sensation data collected from thermal comfort experiments conducted on 1,393 U.S. and Danish subjects in carefully controlled artificial climate chambers [15]:

$$PMV = [0.303\exp(-0.036M) + 0.0275]L \tag{1}$$

where M is the metabolic rate of the human body, W/m^2; L is the heat load of the human body, defined as the difference between the amount of heat produced by the body and the amount of heat dissipated to the outside world.

Considering the diversity of individuals at the physical, physiological, and psychological levels, Fanger recognized that PMV only approximates how most people feel about heat in the same environment. Therefore, he introduced PPD as an indicator to assess people's level of dissatisfaction with specific thermal environments and established a link between PMV and PPD. The formula is as follows [16]:

$$PPD = 100 - 95\exp(-0.03353PMV^4 - 0.2179PMV^2) \tag{2}$$

From the preceding equation, it can be observed that even if PMV=0, roughly 5% of people are unsatisfied with the environment they live in. The PMV-PPD metric has become a common metric for describing and evaluating thermal environments, and its prediction is better for traditional steady-state air-conditioned buildings, but some studies have shown that in standard air-conditioned environments such as residences, due to individual dress and behavioral adjustments, the range of actual comfort temperatures is often wider than that predicted by PMV-PPD models [16]. Therefore, corrections to these models are necessary.

3.3.2 Standard Effective Temperature (SET*)

SET* is the consistent temperature of a person wearing standard clothing and at the appropriate activity level under 50% relative humidity and isothermal conditions, when having the same skin temperature and humidity as the test environment. Its thermal model is based on two coupled heat balance equations [17]:

$$S_{cr} = M - W - (C_{res} + E_{res}) - (t_{cr} - t_{sk})(5.28 + 1.163skbf) \tag{3}$$

$$S_{sk} = (t_{cr} - t_{sk})(5.28 + 1.163skbf) - (C + R + E_{sk}) \tag{4}$$

where S_{cr} and S_{ck} are the heat storage rates of the core nodes and skin nodes, W/m^2; C_{res} and E_{res} are the convective and evaporative heat losses during respiration, W/m^2; t_{cr} and t_{sk} are the core node temperatures and the mean skin temperatures, °C; $skbf$ is the peripheral blood flow, L/hm^2; whereas the skin sensible heat losses due to convection, radiation, and evaporation are given by C, R, and E_{sk}, respectively.

Based on the heat balance equation and inputting parameters such as air temperature, wind speed, relative humidity, metabolic rate, and average radiation temperature, the model is able to calculate the average skin temperature. SET* synthesizes the relationship between environmental factors and the human physiological response, and elucidates how convection and radiation affect the skin temperature and thermal perception. This research directs us to obtain comfort in thermal situations by managing radiation and convection, while having the ability to conserve energy. However, models require several input variables, relying on computers for sophisticated computations, and measurements demand a high degree of accuracy, but sometimes directional measures from sensors may not fully reflect the genuine human experience.

3.3.3 Wet Bulb Black Globe Temperature (WBGT) and Discomfort Index (DI)

WBGT is a measure of human exposure to heat and humidity and is calculated by weighting the natural wet bulb temperature (t_{nw}), the black bulb temperature (t_g), and the dry-bulb temperature (t_a):

$$WBGT = 0.7t_{nw} + 0.3t_g \tag{5}$$

$$WBGT = 0.7t_{nw} + 0.2t_g + 0.1t_a \tag{6}$$

where the formula 5 is utilized for calculating when there is an absence of solar radiation, while the formula 6 is employed for calculation in the presence of solar radiation.

These measurements are easy to obtain and are often used to determine the maximum safe time for hot work. However, the WBGT is poorly predicted when sweat evaporation is limited, so the effects of clothing and activity levels need to be taken into account [18]. DI takes into account the effect of ambient temperature and humidity on thermal discomfort and is calculated as follows [19]:

$$DI = 0.72(T_d + T_a) + 40.6 \tag{7}$$

$$DI = 0.72(T_d + T_a) - 0.72\sqrt{u} + 0.03J + 40.6 \tag{8}$$

where the calculation formula 7 is applicable in the absence of wind, while the calculation formula 8 is used when there is wind. T_a is the dry bulb temperature of the air, °C; T_d is the wet bulb temperature of the air, °C; J is the solar radiation, W/m^2; u is the wind speed, m/s.

Typically, the DI is set at a threshold of 70, above which the population gets uncomfortable. This index is basic and quick to measure, but due to individual variances, it is only used as a relative reference. In addition, there are other thermal comfort indexes such as long-term thermal comfort indexes and extreme environmental thermal comfort indexes, which are not reproduced here owing to the constraint of the length of the article.

This chapter summarizes a variety of thermal comfort evaluation methods and evaluation indexes, and discusses in depth their theoretical foundations, suitable environments, and their distinct advantages and drawbacks. Given that each of these methods and indicators has its own strengths, future study can further explore novel evaluation methods and indicators with a view to more correctly evaluating and optimizing thermal comfort so as to better satisfy people's comfort needs in varied contexts.

4. Thermal Comfort Improvement Technologies and Strategies

4.1 Ventilation and air-conditioning system design

The design of ventilation and air conditioning systems is crucial to guaranteeing interior thermal comfort by managing temperature, humidity and airflow to achieve an appropriate indoor microclimate. Although traditional heating, ventilation and air conditioning (HVAC) systems are successful in controlling the indoor atmosphere, they frequently come at the penalty of excessive energy usage. Therefore, modern system design focuses more on energy efficiency and sustainability. Zhang et al. proposed an energy-efficient optimization method for stratified ventilation and air conditioning (SVC) systems by adjusting the parameters of indoor environment and air supply rate to improve the PMV model [20]. Hua et al. innovatively integrated a DC brushless motor to a workstation customized air supply system to create an atmosphere akin to natural air, which is much superior than typical mechanical air in enhancing thermal comfort [21].

4.2 Green Building Design

Green building design plays an important role in enhancing indoor thermal comfort by employing passive strategies such as optimizing building orientation, natural lighting and ventilation, which significantly reduces the need for mechanical cooling and heating and improves the adaptability and resilience of the building. Zeng et al. established a method for finding the ideal specific heat of a wall by an inverse analysis and application of the Nd-segment approach, which gives a strategy for the energy-saving design by using solar radiation and natural ventilation [22]; Alvarado et al. designed and tested a passive cooling system with aluminum 1100 as reflector and polyurethane as insulation on a concrete roof, which effectively reduced heat flow through the roof [23]; Li et al. used the response surface method to simulate a new energy comfort optimization model, which achieved multi-objective optimization of building parameters and balanced energy demand and thermal comfort requirements [24].

4.3 New Building Materials and Intelligent Building Technology

With developments in materials science, new construction materials offer enormous promise for boosting thermal comfort. For example, phase change materials (PCMs) can manage indoor temperatures and reduce swings. Evola et al. showed that PCM wall panels can improve summer comfort in lightweight buildings [25]. Transparent insulating materials combine light transmission and thermal insulation qualities to increase window energy efficiency. Xin created a porous nano-SiO_2 layer for solar glazing, which achieved a high light transmission rate of 94.3%, delivering considerable environmental benefits [26].

The development of smart building technology further drives personalization and optimization of thermal comfort by enabling real-time monitoring of indoor and outdoor environments through sensors, control systems, and artificial intelligence, automatically adjusting HVAC systems to meet individual needs, improving energy efficiency, and creating customized comfort environments.

The design of ventilation and air-conditioning systems, green building design, the application of novel building materials and the development of intelligent building technologies have all contributed to increasing interior thermal comfort and creating a sustainable built environment. The coordinated application of these technologies and practices not only enhances occupant comfort but also reduces energy consumption, offering both economic and environmental benefits. These solutions need to be continuously adjusted in the future to react to environmental changes and provide healthier, more efficient and environmentally friendly living areas.

5. Conclusions

In summary, thermal comfort research has revealed the close connection between the human body's perception of and adaptation to environmental temperature and psychological and physiological factors. The current research tackles the following challenges: 1) the models produced under laboratory conditions differ from real life, with a narrow range of comfort temperatures, making it difficult to adapt to people from varied cultural backgrounds. How to integrate field research with steady-state evaluation methodologies to increase accuracy is a topic that has to be addressed in the field of built environment; 2) standard sensors cannot adequately record the small changes in dynamic thermal surroundings, which impacts the accurate assessment of human thermal comfort; 3) due to the complexity of human physiology and psychological subjectivity, there are still blind spots in the study of human physiological and psychological reactions and their interaction with subjective temperature sensations, which affects the predictive modeling accuracy of the prediction model.

Therefore, future research will focus on developing an accurate and trustworthy thermal comfort assessment methodology for building types in diverse climates and constructing databases including thermal comfort data. This will require the use of internet and big data technologies to perform dynamic monitoring, alter plans, and optimize controls. At the same time, the development of new environmentally friendly construction materials is a crucial strategy to meet the dual goals of interior thermal comfort and energy savings.

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