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Human Thermal Comfort Theory and Its Role in Modifying Personalized Space Temperature Design

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Abstract: Thermal comfort theory plays an important role in creating a comfortable and healthy building thermal environment and achieving energy savings in buildings. This paper summarizes the development process of thermal comfort theory, and discusses the local-overall thermal comfort effects of personalized comfort systems (PCS) in a non-uniform thermal environments. As a technical means of precise thermal adjustment, PCS can reduce the background temperature of air conditioning during heating, enabling personalized space temperature design, and achieving the goals of comfort, energy savings, and health.

Keywords: thermal comfort theory, personalized comfort system, personalized space temperature design, precise thermal adjustment

1. Introduction

In recent years, thermal comfort, defined as subjective satisfaction with the surrounding thermal environment under the influence of physical, physiological, and psychological factors, has become a major research focus. Research is no longer limited to the study of uniform steady-state thermal environment thermal environments, but now extends to non-uniform dynamic thermal environments. Regarding non-uniform thermal environments, some scholars have studied the local thermal comfort of the human body and its influence on overall body thermal comfort, in order to address thermal comfort issues at the individual scale [1]. Regarding dynamic thermal environments, some scholars have explored the differences between natural wind and mechanical wind to explain the phenomenon of thermal pleasure in the natural environment[2]. Concerning the relationship between the thermal environment and health, other scholars have examined the health drawbacks of uniform steady-state thermal environments and the health benefits of moderate exposure to cold and heat[3].

With the development of research on human thermal comfort research, the personalized comfort system (PCS), a system based on the theory of local thermal comfort for humans and capable of creating a microenvironment for the human body through functions such as localized heating, cooling, or ventilation, has gained increasing attention as a technology for providing "precise thermal service" at the individual scale. Indoor occupants can control their microenvironment through PCS. When the background environment does not meet individual comfort needs, personal thermal comfort can be achieved through local temperature regulation. This not only satisfies individual thermal comfort requirements but also reduces the thermal load on the air-conditioned environment, thereby lowering overall energy consumption. PCS has been widely applied in various settings, such as indoor office environments[4] and outdoor activity areas[5].

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Since the 20th century, the development of human society has faced several challenges: the rapid growth of energy consumption, the unprecedented levels of carbon emissions, and the difficulty of controlling rising global temperatures. Heating, ventilation, and air conditioning (HVAC) energy consumption, as a major source of the main energy consumption, has been slow to achieve significant energy savings. HVAC systems work throughout the entire spaces to create a uniform steady-state thermal environment, resulting in energy waste as they heat or cool areas that are not occupied by individuals. Additionally, these systems cannot meet the thermal comfort needs of different individuals[6]. The use of HVAC systems alone cannot effectively balance thermal comfort needs with energy-saving goals.

To reduce energy consumption in HVAC systems, it is essential to explore the energy-saving applications of PCS in indoor air-conditioned environments. The focus of this research is to study how to leverage the localized effects of PCS to achieve both local and overall thermal comfort for the human body, reduce the dependence of the thermal environment on the background temperature of air conditioning, and design personalized space temperatures that provide good comfort and energy-saving effects, is the focus of this research.

2. Human Thermal Comfort Theory

Research on human thermal comfort began in the early 20th century. As the research progressed, scholars conducted studies from various perspectives, as illustrated in the figure below.

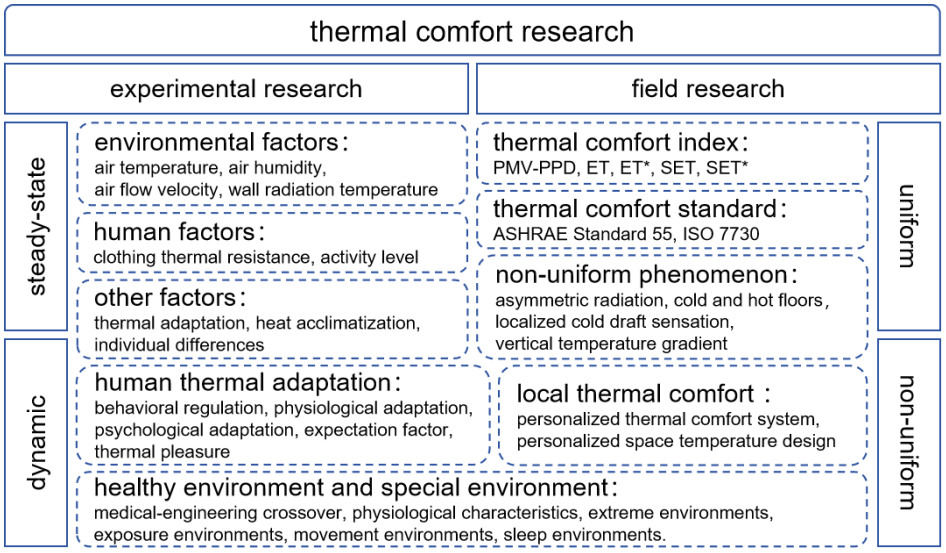

Figure 1: Research related to thermal comfort

Thermal comfort research mainly includes experimental research and field studies. The thermal environment can be divided into steady-state and dynamic thermal environment research, as well as uniform and non-uniform thermal environment research[7]. Thermal comfort research has led to the development of many practical indicators and standards. Currently, scholars focus on various factors, analyzing the thermal comfort characteristics of the human body in different environments.

2.1. Uniform Steady-State Thermal Environment

In 1902, Willis H. Carrier created the first air conditioning system, enabling humans to control indoor temperatures. In 1919, the American Society of Heating and Ventilating Engineers (ASHVE) established the first microclimate laboratory to study the impact of air temperature, humidity, and air flow on comfort. By 1963, the American Society of Heating, Refrigerating, and Air-conditioning

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Engineers (ASHRAE) had gathered data on clothing insulation and metabolic rates at Kansas State University, laying the groundwork for thermal comfort standards.

In the 1970s, Fanger, at the University of Kansas, based on the basis of experimental data, developed research on indoor air conditioning environments using the human thermal balance equation and the ASHRAE 7-scale PMV-PPD model[8][9]. The model integrates four physical variables related to human body thermal comfort (air temperature, relative humidity, air flow rate, and wall average radiation temperature) and two personal variables (clothing thermal resistance and human activity), improving the prediction of the heat-neutral temperature range for thermal comfort in air-conditioned environments.

Since the 1920s, in addition to the PMV-PPD model, other thermal comfort indicators have been proposed, such as the Effective Temperature (ET)[10], New Effective Temperature (ET*)[11], Standard Effective Temperature (SET) [12], and New Standard Effective Temperature (SET*)[13].

In 1966, ASHRAE released the first thermal comfort standard, the ASHRAE Standard 55. This standard successively used the Effective Temperature, New Effective Temperature, and Operating Temperature as the evaluation indices for the indoor thermal environment. In 1984, the International Organization for Standardization (ISO) developed the international standard ISO 7730 based on Fanger's research[14]. In 2004, the revision of ASHRAE Standard 55 revision also recommended using the use of PMV and PPD indices to predict the thermal comfort in air-conditioned environments[15], which is still in use today.

Since the PMV-PPD index does not adequately consider factors such as building type, human thermal adaptability, perceptual control, and thermal experience, the ASHRAE 55 standard based on the PMV-PPD model has poor predictive performance for thermal comfort in actual non-uniform, non-steady thermal environments.

2.2. Non-Uniform Thermal Environment

The causes of non-uniform thermal environments include the non-uniform temperature distribution of indoor air temperature in the vertical direction and the non-uniform physiological characteristics of the human body [16]. In real life, thermal non-uniformity is often caused by factors such as asymmetric radiation, localized cold drafts, vertical temperature differences, and cold or hot floors.

The theory of local thermal comfort theory was developed in the study of a non-uniform thermal environments. In 2003, Zhang at the University of California, Berkeley, Zhang[1] studied the impact of 19 local heat exposure areas on thermal comfort in a non-uniform air supply non-uniform environment. He established a prediction model for local skin temperature, the local skin temperature, and the local thermal comfort, with local heat sensation as the key variable. This model expanded to predict thermal sensation and thermal comfort prediction model from the local to the whole body.

The localized thermal comfort theory has led to the study of personalized comfort systems and the design of personalized space temperatures. In 2016, Ren Yuting et al.[4] created a non-uniform thermal environment in a workstation using air conditioning. Subjects underwent human thermal response experiments in the work area, which were divided into two seasonal conditions (winter and summer) and three localized stimulation conditions (head stimulation, chest stimulation, and hand stimulation). Each sub-condition included several different background temperatures, stimulation temperatures, and wind speeds. The experiments concluded that the overall equivalent temperature in summer was approximately 30°C, and in winter, it was around 24°C—both within the comfort range. However, the comfortable temperature range for different body parts (with an 80% satisfaction rate) varied.

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2.3. Dynamic (Unsteady-State) Thermal Environment

The environmental parameters of a dynamic thermal environment change dynamically over time. Dynamic thermal environments include natural ventilation environment, dynamic air supply environment, and temperature fluctuation environments.

2.3.1. Natural Ventilation Environment

In 1998, de Dear and Brager, based on the thermal comfort database ASHRAE RP-884, proposed the thermal adaptation model for natural ventilation buildings [17][18]. They suggested that human thermal adaptation can occur in three ways: behavioral adjustment, physiological adaptation, and psychological adaptation.

In 2002, Fanger et al. proposed the concept of the expectation factor (also called the expectancy factor, denoted as e) to modify the PMV model[19], making the PMV model is also applicable to non-air-conditioned buildings, such as those with natural ventilation environment.

In 2021, Zhu Yingxin[9] argued that the expectation factor e was insufficient to explain the comfort temperature deviation between natural ventilation environments and air-conditioned environments. He proposed that dynamically changing natural winds could cause comfort temperature deviations, leading to a sense of "thermal pleasure" for people.

2.3.2. Dynamic Air Supply Environment

A dynamic air supply environment can produce airflow sensations (or air feeling). Early research on dynamic air supply environments focused on the discomfort caused by wind blowing. In 1989, Fanger proposed the percentage of unsatisfactory dissatisfaction caused by wind temperature, wind speed, and turbulence in a neutral cold environment[20].

In recent years, studies have shifted to exploring the improvement effect of air blowing on human thermal comfort. In 2016, Chen Dongyang et al. studied the impact of local airflow on human thermal comfort in the summer. Through experiments, they found that both the thermal sensation and the perception of airflow are affected by the local airflow. Environmental temperature and local wind speed significantly improve thermal sensation, while the area where the wind is directed has an effect on thermal sensation, though this effect is not significant[21].

2.3.3. Temperature Mutation Environment

The temperature mutation environment is a special type of dynamic environment. In 1967, Gagge et al. [22] first studied the two types of temperature mutations: "neutral-thermal-neutral" and "neutral-cold-neutral." They observed the phenomena of "transcendence" and "lag" in thermal sensation. Later, in 1993, de Dear[23] also identified the "transcendence phenomenon" in heat sensation also, and discovered the asymmetry in the thermophysiological state of the human body when transitioning from a hot to a cold environment.

In recent years, domestic scholars have also conducted related research. In 2021, Li Nianping et al.[24] studied the impact of "slightly cool-neutral" temperature mutations under radiant air-conditioning conditions on human thermal comfort. By creating two experimental rooms—Room 1 (a convective thermal environment) and Room 2 (with three different air-conditioning conditions, including convective, radiant floor, and radiant ceiling)—they achieved temperature mutations for subjects during spatial transitions. They also discovered hysteresis and psychological anticipation phenomena using dynamic radiant floors.

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2.4. Other Thermal Comfort Studies

In addition to the above-mentioned thermal comfort research, scholars have also conducted studies on human thermal adaptability[25], the psychological role of human perception, long-term thermal history[26], and individual differences, among other topics, thereby filling the theoretical gaps in thermal comfort theory across various fields.

3. Thermal Environment and Health

The intersection of medicine and engineering, focusing on human health issues, is a growing trend in the creation of thermal environments. With the prevalence of air conditioning sickness, scholars are increasingly questioning whether the creation of uniform steady-state thermal environments is truly healthy. A growing number of scholars are now exploring how to improve human comfort and health in natural environments and special environments, such as extreme conditions, exposed environments, exercise environments, and sleep environments.

Research by domestic scholars, such as Zhu Yingxin[2], has concluded that the creation of natural environments and exposure to cold and heat have a positive impact on human health, offering new insights for the development of healthy environments.

With the advancement of this research, more and more other scholars have begun to combine the thermal environment with human immunity, metabolic conditions, and various diseases [27][28].

4. Personalized Comfort System (PCS) — A New Technology Based on Human Local Thermal Comfort Theory

4.1. Proposal of Personalized Comfort System

The Personalized Comfort System (PCS) was first proposed by Zhang Hui at the University of Berkeley in California, Berkeley. Currently, the personalized comfort system is not clearly defined, which is similar to technologies such as station air conditioning (TAC), personalized ventilation (PV), personalized environmental control systems (PECS), or personalized thermal management systems (PTMS)[29].

The personalized comfort system can heat or cool specific parts of the body, requiring less energy to create a microclimate environment, which can ensure that ensures the user can accept the current thermal comfort level and adapt to the existing thermal environment. In recent years, many scholars have considered PCS as an effective means to address the "discomfort phenomenon caused by cold and heat exposure," and many scholars have integrated PCS with the background temperature of air conditioning to achieve reliable energy savings.

At present, due to varying functional needs, several types of personalized comfort systems have been developed. The table below lists several common types of PCS devices.

Table 1: Several Common Types of PCS [30]

type	heating type					cooling type		
name	heating seats	foot warmers	hand warmers	radiant panels	heating clothing	fans	cooling seats	air conditioning
example								

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4.2. Some Research on Personalized Comfort System

In 2019, the Hong Kong Polytechnic University team [31] developed a new hybrid personal cooling jacket (HYB) based on dry ice and an air ventilation fan to study its cooling effect on the mascot wearer during moderate-intensity activities in hot and humid environments. The experiment showed that the HYB could reduce the risk of heat stress in hot and humid conditions, preventing the core temperature of the mascot wearer from rising above 38.0°C, thus maintaining their working performance. In the same year, Yang Hecheng et al.[32] used electric thermal cooling clothes to study the effect of a single part of the cooling specific parts of the trunk area in a hot indoor environment on thermal comfort. In the experiment, 20 subjects underwent local cooling of different trunk areas such as the chest, abdomen, upper back, and lower back. The results showed that local cooling of the trunk can significantly improved the overall heat sensation and thermal comfort of the subjects in a high-temperature environment.

During the 2022 Beijing Winter Olympics, a team from Tsinghua University [33] conducted experiments in an outdoor cold race-watching environment (15-5°C) and studied the feasibility and effectiveness of local heating devices, such as heating gloves, heating insoles, and heating backrests, in improving the thermal comfort of spectators in the cold environments. The experimental results showed that the improvement effect of the local heating of the hands, feet, and waist improved comfort for both seated and standing spectators. During the same period, Li Sishi et al.[34] from Tsinghua University conducted research on a wearable personalized thermal comfort system suitable for cold environments. They developed a heating vest that provides functions such as precise temperature control and intermittent alternating heating.

4.3. The Significance of the Personalized Comfort System in Personalized Space Temperature Design

From the perspective of comfort and energy savings, the personalized comfort system can improve the human microenvironment by adjusting both the background temperature of the surrounding space of the human body and the local heating or cooling temperature applied to the human body. In other words, it can design a personalized space temperature that meets the requirements of human thermal comfort and energy savings, thus optimizing system performance.

From a long-term health perspective, the personalized comfort system facilitates the design of personalized space temperatures, which helps prevent the human body from being confined to the uniform, steady thermal environment created by conventional air conditioning systems. It relaxes the thermal comfort temperature range of the air-conditioned environment, allowing the human body to appropriately receive cold and heat exposure—either locally or as a whole—thereby enhancing thermal adaptability.

5. Specific Guidance of Human Thermal Comfort Theory for Personalized Space Temperature Design

5.1. Application of Personalized Comfort System at Lower Air Conditioning Background Temperature

In 2019, Li Jia [6] developed the local thermal comfort theory for the human body, and studied the positive role of the personalized comfort system (PCS) in improving the thermal comfort levels and reducing energy consumption. The research involved a personalized heating device combined with an electric heating cushion and a foot heating plate, which could eliminate the local discomfort in the buttocks, thighs, and feet by heating the human microenvironment.

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Figure 2: Distribution of PCS



Figure 3: PCS Heating Equipment Physical Picture

To study the thermal comfort of the human body under personalized heating, Li Jia conducted controlled experiments with 18 college students conduct control experiments in experimental rooms with background temperatures of 14°C, 16°C, and 18°C. The subjective evaluation results of the experiments indicated that with the use of personalized heating devices, the overall thermal sensation gradually approached neutrality, and the degree of thermal comfort gradually increased. Local thermal sensation and thermal comfort were related to both the background temperature and the degree of heating. Among the three heated areas, the feet and buttocks were less affected by the background temperature and maintained thermal comfort in the cold environments, while the thighs were more affected by the background temperature. The interaction of thermal sensations from multiple areas determined the overall thermal sensation. Personalized heating expanded the acceptable temperature range, and under the effects of electric heating cushions and foot warmers, more than 80% of the subjects indicated they could accept an indoor environment of 14°C.

To study the energy consumption of the system under the action of personalized heating, Li Jia established a room model using EnergyPlus and set relevant parameters in order to simulate the energy consumption of the two air conditioning systems during the winter design day and heating season at different temperatures. The energy consumption of heating season at a room temperature of 20°C was selected, and the energy savings from individual heating equipment were analyzed. The results show that the personalized heating equipment can reduce the indoor heat load, and its lower power consumption affects the background air conditioning energy consumption. Compared to the energy consumption of a room temperature of 20°C and separate air conditioning alone, when the room temperature control is controlled at 14°C, energy savings of 39.6% and 42.3% were observed during the heating season. The energy saving rate increases as the decrease of room temperature decreases. For every 1°C reduction in indoor temperature, the average energy saving is about 7%.

However, there are still many shortcomings and areas for improvement in the application of this technology. The study used college students as the subjects, raising questions about the applicability to special groups such as children and the elderly. The combined use of the electric heating seat

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cushion and foot heating board did not consider the human thermal comfort and energy-saving effects of each piece of the equipment alone. Furthermore, it did not address the connection between human skin temperature and human thermal comfort, reflecting only reflects the heating effect through subjective feelings and lacking a mechanism for integrating medical and industrial research. The subjective reaction experiment also failed to deeply consider the effects of indoor relative humidity, indoor wind speed, and perceived air quality changes on the human body, resulting in a lack of comprehensiveness.

The study, through experiments and simulation analysis, demonstrates that PCS can lower the background temperature of air conditioning, achieve personalized spatial temperature design, and meet the needs of both human thermal comfort and energy consumption.

5.2. Personalized Indoor Space Temperature Design in Winter Based on Thermal Environment Adjustment Mode, Heating Mode, and Personnel Activities

In 2024, Chen Shuqin et al. studied the thermal comfort and heating energy consumption of Hangzhou residents using PCS during winter. The study considered residents' various thermal environment adjustment modes, heating modes, and personnel activities, analyzing the impact of heating equipment and human metabolism on thermal comfort. Based on surveys and cluster analysis, the research identified the thermal comfort characteristics and typical heating modes for Hangzhou residents in late winter and early winter. Simulation results indicated that the neutral temperature for different heating modes and activities ranged from 13.9°C to 18.8°C, with a comfort temperature range of 11.0°C to 20.5°C. The comfort level in living rooms varied between 43.74% and 80.21%, while in bedrooms it exceeded 70%. Energy consumption analysis showed that heating energy intensity for typical buildings at the end of winter and early winter was 1.28 kWh·m², increasing to 13.06 kWh·m² during severe winter.

In winter, due to individual differences in residents' habits for thermal environment regulation and personnel activities, the actual thermal regulation patterns deviate from the typical thermal regulation models proposed by scholars. Therefore, personalized spatial temperature design is necessary. That is, residents can choose appropriate thermal regulation modes based on their activity status, indoor climate conditions, room temperature, humidity, wind speed, and energy consumption needs, to control both the indoor thermal environment and the microenvironment around the human body.

6. Conclusion

Uniform steady-state thermal environments have their inherent drawbacks. Therefore, this paper actively explores the role of PCS in personalized spatial temperature design under the guidance of local thermal comfort theory. The following is a summary of this paper:

1. In the first and second sections, the article mainly introduces the development of thermal comfort research and its technological orientation.
2. In the third section, the article discusses the relationship between the thermal environment and health. It points out the inherent health deficiencies of a steady-state thermal environment, the thermal pleasure effects of the natural environment, and the specific environmental effects on special needs. The article also highlights the positive effects of natural sensation and exposure to cold and heat on improving the level of human health.
3. In the fourth section, the article briefly introduces PCS technology, emphasizing its positive role in personalized precise thermal services. It also briefly introduces some research on PCS applications in clothing and outdoor settings. Finally, focusing on the most important indoor air-conditioning environment, the article discusses the comfort, energy-saving, and health significance of PCS in personalized spatial temperature design.

4. In the fifth section, the article explores the specific corrective effects of PCS, based on the local thermal comfort theory, on personalized space temperature design. It was found that under lower background air-conditioning temperatures, the personalized space temperature design triggered by PCS has a significant impact on human thermal comfort and energy savings. It was also found that the adjustment modes of the thermal environment, heating methods, and human activities reflect the thermal comfort characteristics and heating energy needs of residents in winter, thereby affecting the design of personalized space temperatures.

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