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Thermal Comfort Simulation in Furniture Design: Integrating Considerations of the Building Thermal Environment

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ABSTRACT

As demands for the quality of living environments increase, thermal comfort in furniture design is garnering attention. Studies indicate that furniture should not only meet basic functional and aesthetic requirements but also influence indoor thermal environments and interact with human thermal exchanges, which are crucial for optimizing living comfort. This research aims to explore how thermal comfort in furniture design can be integrated with the building thermal environment to enhance indoor comfort and energy efficiency. Existing studies predominantly focus on surface treatments of furniture, with a lack of comprehensive analysis on the material's contact thermal sensation, the thermal properties of furniture, and their performance under varying building thermal conditions. Addressing this gap, this paper proposes a comprehensive research framework consisting of three main components: first, analyzing the impact of the building thermal environment on furniture thermal comfort; second, designing furniture with consideration for material's contact temperature sensation; and finally, developing furniture heat release rate curves suitable for different building thermal environments. This series of studies not only enhances the scientific and practical aspects of furniture design but also provides new theories and methods for the field of architectural design.

1. INTRODUCTION

In modern architectural design, thermal comfort has become one of the important indicators of indoor environmental quality [1-5]. As the standard of living improves, the demand for indoor comfort also increases, especially in the field of furniture design, where the consideration of thermal comfort becomes particularly important [6, 7]. Furniture needs to not only satisfy functionality and aesthetics but also consider its impact on the indoor thermal environment and its thermal exchange with the human body [8-10]. Additionally, the thermal environment of the building also significantly impacts the thermal comfort of furniture, and how to effectively integrate the two to optimize the indoor environment is the focus of this research.

Studying thermal comfort in furniture design and integrating it with the architectural thermal environment can not only enhance the comfort of living and usage but also improve energy efficiency and promote environmental sustainability [11, 12]. Moreover, this field of research is significant for improving human health and enhancing the quality of life, especially in living environments under extreme climate conditions [13-16]. By optimizing furniture design, it is possible to effectively regulate indoor temperatures, reduce energy consumption, and simultaneously increase the satisfaction and comfort of occupants.

However, current research on thermal comfort in furniture design is mostly limited to surface studies and lacks in-depth systematic analysis and comprehensive consideration [17-19]. Existing research methods often overlook the thermal perception differences between furniture materials and human contact, as well as the impact of furniture thermal characteristics on the overall thermal environment of the building [20, 21]. Additionally, research on the heat release rates of furniture is also insufficient, lacking precise data support and theoretical models, which limits the scientific and practical aspects of thermal comfort design.

To overcome these shortcomings, this paper proposes a comprehensive research framework that covers three main research contents: first, an in-depth analysis of the building thermal environment's impact on furniture thermal comfort; second, designing furniture considering the temperature sensation of material contact to improve thermal comfort; and finally, fitting heat release rate curves of furniture suitable for different building thermal environments. These studies not only provide new theoretical guidance and practical application possibilities for furniture design but also offer innovative ideas and methods for the field of architectural design, having significant theoretical and practical value.

2. FURNITURE DESIGN AND BUILDING THERMAL COMFORT ANALYSIS

In the traditional ASHRAE 55-1992 comfort standards, thermal comfort is defined as the state of satisfaction with the thermal environment, usually associated with a neutral thermal sensation. However, when considering thermal comfort in furniture design, this definition needs to be specifically adjusted to accommodate dynamic and complex building thermal environments. In this context, thermal comfort is not only related to neutral thermal sensation but also needs to consider how furniture materials, shapes, and layouts interact with the architectural environment, affecting the transfer and distribution of thermal energy. Therefore, when analyzing the building thermal environment, thermal comfort should be viewed as a dynamic state, distinct from thermal sensation, encompassing the comprehensive impact of the interactions between furniture and the environment on occupants' thermal sensation. In furniture design, considering the complex interplay of thermal comfort and the building thermal environment, the traditional ASHRAE 7-point thermal sensation voting scale needs to be appropriately adjusted to better reflect the impact of the interactions between furniture and the environment on individual thermal sensations. Design factors of furniture, such as the thermal conductivity of materials, heat absorption capacity, surface temperature, and the layout and size of furniture, all affect the subjective evaluation of thermal sensation. Thus, the thermal sensation voting values for furniture analysis aimed at building thermal environments should include a comprehensive consideration of these variables, not limited only to air temperature and humidity but also including the temperature response at the contact interface between furniture and the human body.

In furniture design, especially in the comprehensive analysis of building thermal environments, understanding the contact temperature sensation between humans and furniture materials needs to go beyond traditional simple temperature differential interactions. The thermal comfort design of furniture involves not only the thermal conductivity of materials but also considers the temperature regulation of furniture surfaces and the interaction with indoor environmental temperatures. When the human body contacts furniture, the comfortable temperature at the contact site is primarily determined by the difference between the skin temperature of the human body and the furniture surface temperature. This difference should be controlled within a range to avoid producing too strong a sensation of warmth or cold. For example, when the surface temperature of the furniture is close to the physiological neutral of the human body, the user's thermal sensation tends to be comfortable. On this basis, designers need to select appropriate materials and technical means, such as adjusting the thermal properties of furniture surfaces or using temperature control technologies, to ensure that furniture can provide a contact experience close to physiological neutrality under different building thermal environments, thereby optimizing the user's thermal comfort. Additionally, maintaining environmental temperatures within the range of 18-23℃ and relative humidity between 40-60%, along with appropriate consideration of metabolic rates, will further enhance the overall thermal comfort experience during furniture use. This comprehensive approach not only focuses on the absolute values of temperatures but also emphasizes the rate of temperature change and the comprehensive impact of furniture materials on thermal comfort, aiming for more precise and personalized thermal comfort design goals.

3. FURNITURE DESIGN FOR THERMAL COMFORT

Over the years, many studies have focused on the thermal sensations of contact between the human body and different materials, demonstrating that the physical properties of materials significantly influence human thermal sensations. Research indicates that the thermal conductivity of materials is a key factor affecting warmth sensation, with warmth sensation negatively correlated with the logarithmic value of material thermal conductivity and heat flux. Additionally, the thickness of material coatings decisively affects the sensation of warmth or cold; as thickness increases to a certain level, the impact of the substrate's thermal conductivity on warmth or cold sensation diminishes. Moreover, real indoor environment tests have shown that wooden flooring with low thermal conductivity and excellent insulation properties can slow the decrease in skin temperature, thereby providing a better sensation of warmth. These research findings provide important reference data for the selection and design of furniture materials, highlighting the significance of material characteristics in the design process.

Based on the current state of research, the design of furniture thermal comfort considering material contact temperature sensation is particularly important. Through scientifically selecting and optimizing furniture materials, users' thermal comfort can be effectively improved. For example, choosing materials with lower thermal conductivity can enhance the warmth sensation of furniture, and increasing the thickness of materials can reduce the impact of the substrate's thermal characteristics on the surface, thus better controlling the temperature sensation upon contact. Figure 1 displays the relationship curve between wood thickness and the psychological quantity of contact temperature sensation. Furthermore, by studying material contact temperature sensations, furniture designers can more precisely adjust the temperature of furniture surfaces, creating a more comfortable use environment for users. This design approach not only enhances the functionality of the furniture but also improves the overall thermal comfort of the indoor environment, further advancing the depth of thermal comfort research and innovation in furniture design.

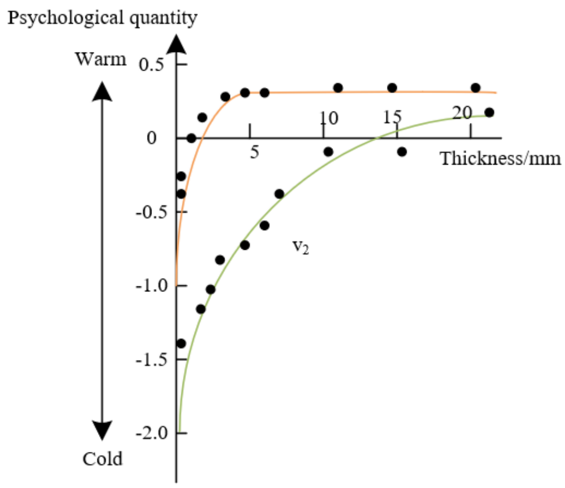


Figure 1. Relationship curve between wood thickness and the psychological quantity of contact temperature sensation

In furniture design, using wood veneer as a facing material to improve and regulate the temperature sensation upon human contact is an effective strategy. Especially in the context of building thermal environment analysis, considering the temperature sensation of contact with wood involves not only focusing on the physical thermal properties of the veneer, such as thermal conductivity and thickness, but also considering how these properties optimize human sensation under different indoor temperatures and environmental conditions. A wood veneer covering on metal or other materials with high thermal conductivity, even if only 1mm thick, can significantly improve the warmth or cold sensation of the substrate. This is because the low thermal conductivity of wood can reduce the rapid transfer of heat to the skin, thereby alleviating discomfort from cold or excessive heat. In indoor environments, this effect can allow furniture users to experience more comfortable temperatures across different seasons and room temperatures. From the perspective of furniture design, this method not only enhances the practicality and comfort of the furniture but also demonstrates the application of thermal environment engineering in furniture design, ensuring that furniture can provide continuous thermal comfort to users in actual use.

In the context of integrating furniture design with the building thermal environment, the relationship between the thermal conduction speed of wooden furniture and the psychological quantity of users' temperature sensation is particularly important. Wood, due to its lower thermal conductivity compared to materials like aluminum or stainless steel, can provide a gentler contact sensation, akin to towels or cotton, making it particularly popular in furniture design. Studies have shown that there is a linear relationship between thermal conduction speed and the psychological quantity of temperature sensation, which has direct practical value for furniture design. Especially for furniture surfaces that have prolonged contact with the human body, such as floors, chairs, and tabletops, using materials with slower thermal conduction speeds, like wood, can significantly enhance comfort and reduce the cold sensation caused by high heat flux. Additionally, the density and porosity of wood also affect heat transfer, and reasonable design and material selection can optimize this transfer process, enhancing thermal comfort. This deep understanding of the relationship between wood's thermal conduction speed and the psychological quantity of temperature sensation enables designers to more precisely adjust furniture materials and structures to suit specific building environments. Figures 2 and 3 show the relationship curves between the initial and long-term heat flow movement speed of furniture and the psychological quantity of temperature sensation.

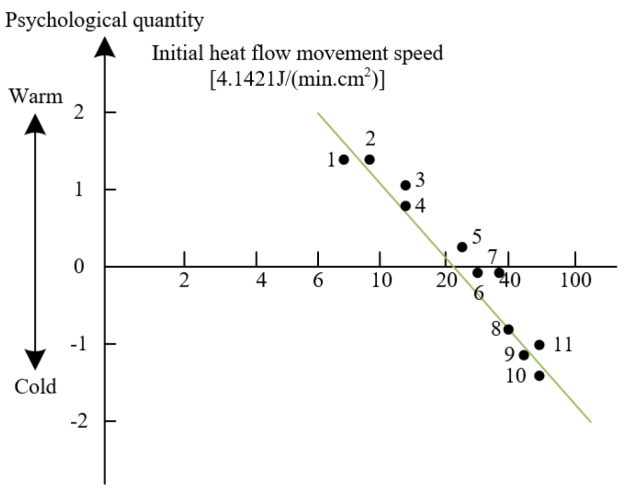


Figure 2. Relationship curve between initial heat flow movement speed of furniture and psychological quantity of temperature sensation

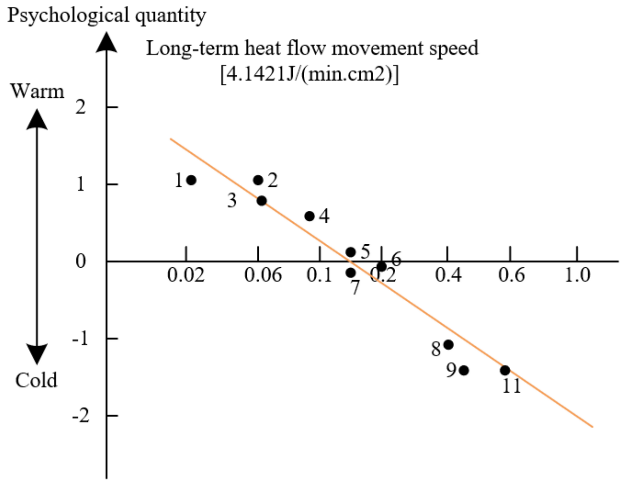


Figure 3. Relationship curve between long-term heat flow movement speed of furniture and psychological quantity of temperature sensation

Further, the thermal conductivity of materials directly affects the thermal sensation of warmth or cold when the human skin contacts furniture, where materials with low thermal conductivity like polystyrene foam and light wood provide higher warmth ratings, whereas materials with high thermal conductivity like concrete offer lower warmth ratings. This relationship directly impacts user comfort and satisfaction. Designers need to consider the thermal conductivity of furniture surface materials to adjust and optimize the thermal interaction with users. In designing furniture, selecting materials with suitable thermal conductivity not only improves thermal comfort but also reduces the rate of heat flow to alleviate the contact cold sensation, especially under indoor environmental conditions. Moreover, considering changes in the building thermal environment, the appropriate selection of furniture materials can further optimize the overall thermal comfort of the living environment, achieving a synergistic optimization of the thermal environment and furniture design.

When considering furniture design and the building thermal environment, it is also necessary to understand the amount of heat movement and heat flux during contact between furniture materials and the human body. The heat flux of different materials is closely related to their thermal conductivity, which directly affects the materials' warmth or cold sensation. For example, wood and man-made boards, materials with relatively low thermal conductivity, slow the transfer of heat from the skin to the furniture, thereby providing a more suitable warmth sensation upon contact. In contrast, materials like metal, concrete, and glass have higher thermal conductivity and greater heat flux, making them feel colder upon contact. In furniture design, choosing materials with appropriate thermal conductivity can significantly improve users' thermal comfort. This material selection not only affects users' immediate thermal sensation experiences but also relates to the energy efficiency and overall thermal stability within the building. Therefore, in furniture design, by choosing and using materials with moderate thermal conductivity, the heat flux in contact with the human body can be effectively controlled to enhance the comfort and functionality of the living space.

To accurately assess thermal comfort, this paper uses thermocouples to monitor the temperature between the skin and furniture material interfaces and employs heat flux sensors to measure the heat flow rate at the contact points, thus accurately capturing the rapid temperature changes immediately after initial contact with furniture materials and the subsequent gradual stabilization process. Materials of different densities and thermal conductivities, such as polystyrene foam, light wood, and high-density wood, respond differently to heat flow rates and interface temperature changes, which directly impact thermal comfort. For example, low-density materials like polystyrene foam provide slower temperature changes, thereby increasing the warmth sensation; whereas high-density materials like oak display a slow temperature decrease, potentially causing a cooler sensation. These detailed temperature and heat flux data not only help understand the thermal performance of different furniture materials in practical applications but also guide material selection and furniture design to optimize the internal thermal environment and enhance the comfort of occupants.

Further, this paper conducts an in-depth analysis of the temperature changes during contact between furniture materials and the human body to reveal the dynamics of thermal exchange after contact between human skin and furniture materials, especially the rapid decrease in skin surface temperature in the initial few seconds and the subsequent stabilization of temperature. Experimental results show that the significant reduction in skin temperature at the beginning of contact leads to a noticeable cold sensation experience due to rapid heat loss. Afterward, the temperature gradually stabilizes, and the slight rise in skin temperature within 60 seconds to 5 minutes after contact may not significantly affect the thermal sensation. This dynamic of heat flow reflects the thermal response characteristics of furniture materials, providing direct guidance for material selection and surface treatment in furniture design.

In furniture design, it is also necessary to consider how the building thermal environment affects the psychological sensations experienced during material contact with the human body. Studies show that people's psychological expectations of different furniture materials before contact affect their sensory responses. For example, contact with fabrics and wood is often associated with a positive psychological state because these materials provide warmer and more comfortable sensations, while contact with metals and stones, due to their high thermal conductivity leading to a cold sensation, often causes slight physiological and psychological discomfort. These responses show significant process changes within the first 30 seconds to 300 seconds of contact, such as the gradual disappearance of the cold sensation from wood and fabrics, while the cold sensation from metals and stones diminishes but remains. In furniture design, understanding these psychological and physiological responses is crucial for selecting appropriate materials to ensure users' thermal comfort and psychological satisfaction. By optimizing material selection and treatment, designers can effectively improve the thermal comfort of the indoor environment, while considering users' psychological feelings and actual sensory experiences, thus achieving better human comfort and practicality of furniture in the design of the building thermal environment.

In summary, the design of furniture thermal comfort directly affects the comfort and health of users in their living or use environments, making it necessary to study this aspect. Through analyzing innovative designs like air-conditioned sofas, electrically heated sofas, and heated seats, we can see that integrating temperature control technologies into furniture design can significantly enhance the user experience. For example, the mini air-conditioning system of an air-conditioned sofa can adjust the seat temperature based on environmental temperature and user needs, while the constant temperature control of an electrically heated sofa ensures a comfortable user experience even in damp or cold environments. These designs not only address the limitations of traditional materials in terms of thermal conductivity but also enhance the functionality and adaptability of furniture. Future furniture design should focus on further integration of thermal comfort with material technology, especially in the analysis of the building thermal environment. The study of heat release rate curve fitting will be a key technology, helping designers predict the thermal behavior of furniture materials under different environmental conditions, thus more precisely controlling temperature changes on furniture surfaces. Through simulation analysis, the thermal response speed of materials can be optimized, ensuring that furniture provides sufficient cooling in summer and necessary warmth in winter. Moreover, as smart home technology develops, furniture integrated with sensors and adaptive control systems will become more prevalent, able to adjust its temperature in real-time to accommodate users' immediate needs and external environmental changes.

4. HEAT RELEASE RATE CURVE FITTING FOCUSED ON BUILDING THERMAL ENVIRONMENT ANALYSIS

This paper focuses on the study of fitting and predicting models for furniture heat release rates and how optimizing materials and design can improve furniture's thermal comfort. The primary reason for selecting upholstered furniture for heat release rate studies includes their widespread use of flammable materials such as polyurethane foam and synthetic fibers, which significantly impact thermal comfort during regular use, especially in terms of heat transfer and regulating environmental temperatures. By analyzing the thermal behavior of upholstered furniture like sofas and mattresses under different environmental conditions, a better understanding and prediction of their contribution to the indoor thermal environment can be achieved. Additionally, this type of furniture often has simpler forms, reducing the interference of design complexity on thermal behavior analysis, thus making the prediction of heat release rates more accurate. Therefore, developing heat release rate prediction models based on these considerations, such as the improved r-model, FFB model, MRFC model, and Hoglander and Sundstorm model, can provide a scientific basis for designing more comfortable and thermally efficient furniture, enhancing the comfort of living and working spaces, as well as improving energy efficiency and environmental sustainability.

Assuming the heat release rate is represented by $\dot{W}$, the reference peak by X, the rising segment factor by Y, the falling segment factor by Z, the peaking factor by o, the reference peak moment by s_{CO}, time by s, and the sampling interval by j, the proposed heat release rate prediction model is given by the following equation:

$$\dot{W}=\begin{cases} X\exp\left[-Y\left(s-s_{CO}\right)^{2}\right] s\le s_{CO} \\ X\exp\left[-Z\left(s-s_{CO}\right)^{o}\right] s> s_{CO} \end{cases} \tag{1}$$

The model design, through the construction of piecewise functions, accurately simulates the dynamic changes in heat release rate over time, thus providing important data support for thermal comfort in furniture design. This model particularly considers the unique thermal comfort characteristics of upholstered furniture in changing building thermal environments, such as using a natural base number time function to describe the growth and decay process of heat release, further adjusted by the rising segment factor Y and falling segment factor Z to modify the steepness of the curve, while the peaking factor o is used to adjust the smoothness or sharpness near the peak, thereby simulating the thermal behavior under different materials and construction conditions. At the same time, the reference peak X is used to set the maximum value of heat release, ensuring that the prediction results match the actual combustion performance. Moreover, the design of the sampling interval j aims to optimize computational efficiency, allowing the model not only to provide scientifically accurate predictions but also to facilitate comparison with field experimental data.

The model is based on an improved version of the Hoglander and Sundstorm model. Key improvements include adjusting the time unit from minutes to seconds to enhance the model's response accuracy to the dynamics of heat release. Furthermore, by modifying the power function in the time expression, the model can accurately reach the set peak X at the predetermined reference peak moment, making the model more accurately reflect the thermal comfort characteristics of materials under actual building thermal conditions. Additionally, by adjusting the rising segment factor Y and falling segment factor Z, the model can flexibly simulate the shape of the heat release rate curve to adapt to different building thermal environments and material characteristics.

The effectiveness and adaptability of the model are achieved by precisely determining and calibrating key parameters such as reference peak X, rising segment factor Y, falling segment factor Z, reference peak moment s, and peaking factor o. These parameters are determined based on detailed fitting of experimental data curves, ensuring that the model can accurately reflect the heat release behavior of upholstered furniture in actual building thermal environments.

Experiments measuring the heat release rate of sofa cushions and sofas, and their fitting results, show that the new model can effectively predict experimental curves, accurately reflecting the trends in heat release rates, which is crucial for optimizing furniture's thermal comfort. Through adjustments in the model coefficients, particularly the setting of the rising segment factor Y, such as Y=0.00081, the rising segment of the heat release rate of the sofa cushion in experiments was successfully simulated, while changes in the falling segment factor Z and peaking factor o showed less regularity, indicating a need for further research to optimize these parameters. Through parameter fitting, the above equation can be adjusted to:

$$\dot{W} = \begin{cases} X\exp\left[-0.00081\left(s - s_{CO}\right)^2\right] s \le s_{CO} \\ X\exp\left[-Z\left(s - s_{CO}\right)^o\right] s > s_{CO} \end{cases} \quad (2)$$

Experiments measuring the heat release rate of sofa cushions and sofas, and their fitting results, showed significant deviations between the model's predicted curves and experimental curves at the start of the steep increase under standard settings (i.e., B=0.00081), indicating an initial delay issue with the predicted curve. By adjusting the rising segment factor Y, reducing it by tenfold to B=0.000081, the accuracy of the fit significantly improved. This demonstrates the critical role of model parameter adjustments in addressing different experimental conditions. This finding emphasizes the need for flexibility and adaptability in heat release rate models when designing upholstered furniture in architectural environments, in order to accurately simulate the behavior of furniture under various building thermal conditions, thereby enhancing the thermal comfort of the furniture. Specifically, the reference peak X and the rising segment factor Y are represented in scientific notation, i.e., $X=x\times10^v$, $Y=y\times10^{-l}$. Assuming the heat release rate during the steep increase phase is represented by W_{ZJ}, the following equation for the rising segment is:

$$\dot{W}_{ZJ} = x\times10^v \exp\left[-y\times10^{-l}\left(s - s_{CO}\right)^2\right] \quad (3)$$

Given an initial value of the heat release rate W_{UB} as 1 kW, substitute into the formula and express it as the reference peak moment s_{CO}:

$$s_{CO} = \sqrt{\frac{LN\left(x\times10^v\right)}{7.7\times10^{-l}}} + s \quad (4)$$

Setting l=0s when W_{UB}=1 kW, then:

$$s_{CO} = \sqrt{\frac{LN\left(x\times10^v\right)}{7.7\times10^{-l}}} \quad (5)$$

Further simplification of the above equation results in:

$$s_{CO} = 0.36\sqrt{\left(LNx + 2.3v\right)\times10^l} \quad (6)$$

In the above equation, if $1\le x<10$, then $0\le LNx<LN10$ and $LIM_{x\to10}(LNx)\approx2.311$, so under the premise of certain l and v, the range for the reference peak moment s_{CO} is $0.36\sqrt{2.3n}\times10^l\le s_{CO}<0.36\sqrt{2.3(v+1)}\times10^l$. This range of values becomes meaningful when $l\ge3$ according to practical application needs.

Considering v=5, where the reference peak exceeds 100 MW, this clearly meets most building thermal environment requirements, and when the maximum value of s_{CO} is 133 seconds, it indicates that the model can effectively cover scenarios of rapid heating or cooling. For example, when v=2, the reference peak is between 100 kW and 1000 kW, and the heat release rate's rising time is between 78 and 90 seconds, ensuring the model's accuracy within this range. This shows that the setting of the rising factor B=0.00081 is suitable for predicting scenarios where the steep increase time is less than 145 seconds. If the steep increase time of heat release rate changes exceeds this upper limit in actual applications, it may lead to significant prediction errors. Therefore, studies on the heat release rate of upholstered furniture oriented towards building thermal environments should focus on the model parameter's range of adaptation, and how to adjust model parameters to optimize prediction accuracy for different building thermal environments. This provides scientific data support for furniture design to enhance the thermal comfort of furniture, ultimately achieving a more comfortable and practical indoor environment design.

5. EXPERIMENTAL RESULTS AND ANALYSIS

From the experimental data shown in Figure 4, it is evident that the type of furniture material significantly affects the changes in skin temperature after contact with the human body. The temperature change curves for fabric and wood materials show that their temperature changes are relatively mild; after 360 seconds of contact, the temperature slowly decreased from an initial 33.5°C to 32.8°C and 32.4°C, respectively, and then gradually rose to 33.8°C. This indicates that fabric and wood have better thermal stability and the ability to regain temperature, which is crucial for maintaining contact comfort. In contrast, plastics, stone, and metals show a more drastic temperature drop, especially stone and metal, which quickly drop to 28.2°C and 28.0°C within the first 60 seconds, indicating higher thermal conductivity and rapid heat dissipation. Although the temperature of stone and metal gradually recovers over time, overall, their ability to regain temperature is weaker, which may lead to lower thermal comfort. These experimental results clearly demonstrate that the thermal performance of furniture materials significantly impacts the perceived temperature and thermal comfort of the human body. Fabric and wood, due to their slower temperature changes and better insulation properties, provide higher thermal comfort for users. Although plastics, stone, and metals may have advantages in aesthetics and durability, their rapid temperature changes and lower insulation capabilities may cause discomfort in cold environments, especially when in direct contact with the skin. Therefore, this study, through the analysis of the thermal performance of different materials, validates the importance of considering material contact temperature sensation in furniture design, which directly contributes to enhancing the thermal comfort and overall environmental quality inside buildings.

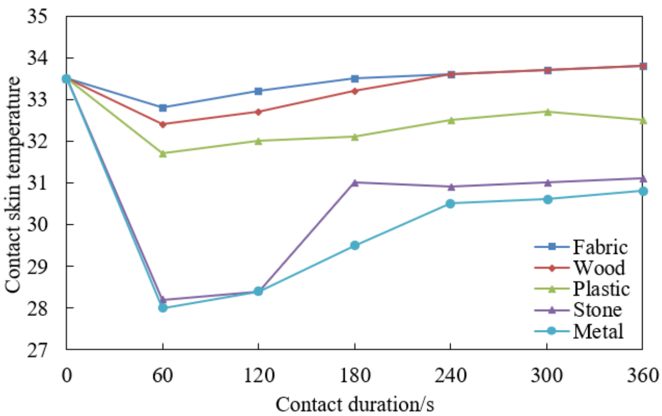


Figure 4. Changes in skin temperature during contact with furniture materials

According to the experimental results of this paper, as shown in Figures 5 and 6, in most experiments on the thermal comfort of upholstered furniture, the proportion of heat released during the rising segment of the heat release rate typically falls between 25% and 35%. This range implies that in different building thermal environments, upholstered furniture releases a significant portion of heat during the initial segment of heat release. Further analysis of this data suggests that management and control of this initial heat release phase become particularly important in furniture design and architectural environment planning. From these experimental data, we can determine that the constant for the proportion of heat released during the rising segment is 30%, which is the average value between 25% and 35%, providing us with a reference for further model fitting and architectural design optimization. In furniture design and building environmental setup, proper control and management of this segment of heat release can significantly improve the safety and thermal comfort within the building. This also shows that in furniture design, selecting appropriate materials and construction can effectively regulate and control the heat release rate, thus optimizing furniture safety and thermal comfort.

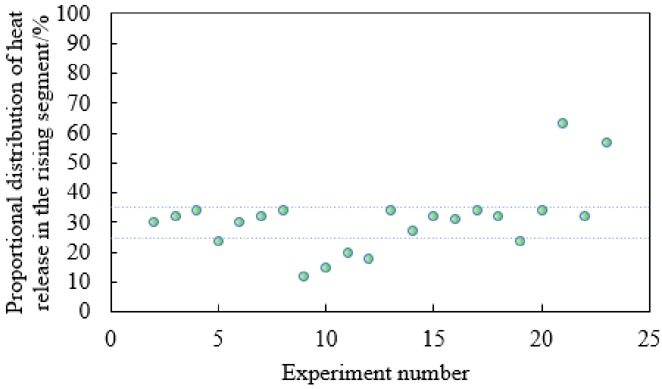


Figure 5. Proportional distribution of heat release in the rising segment of furniture

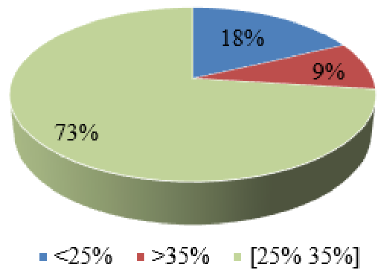
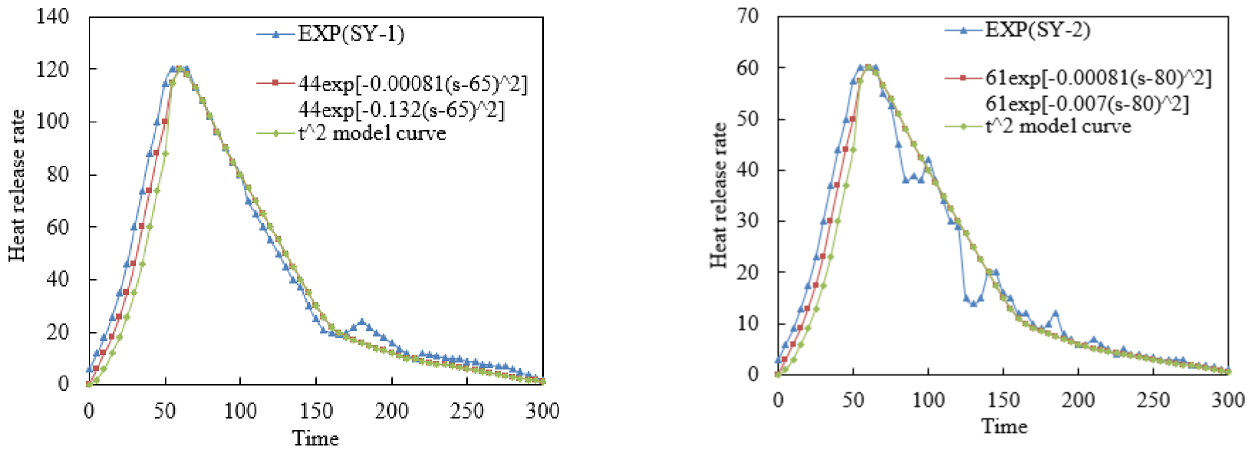


Figure 6. Graph of heat release rate proportional distribution in the rising segment of furniture

From the data displayed in Table 1, the reference peaks and peak moments of the six different experimental samples (*SY*-1 to *SY*-6) show significant variation, reflecting the different behaviors of various sofa cushion materials and structures in fire simulations. The range of reference peaks from 57 to 989 reveals substantial differences in the combustion intensity of different materials; the lowest peak occurs in experiment *SY*-2, while the highest is recorded in *SY*-6. This variation could be determined by the combustibility, density, and other combustion characteristics of the materials. Peak moments also vary from 54 seconds to 129 seconds, further indicating the time differences each sample takes to reach maximum heat release rate. The rising factor remains consistent across all experiments (0.00078), indicating a uniform method to assess the speed of increase in heat release rate. The falling factor and peaking factor are adjusted according to the specific combustion characteristics of each sample, ranging from 0.007 to 0.024 and 0.9 to 1.458 respectively, reflecting individual differences in cooling speed and peak adjustment of different materials. The analysis of these data not only shows the diversity of thermal behavior of sofa cushions during combustion but also validates the effectiveness of fitting the heat release rate curves with different parameter values. Through precise model fitting, a better understanding of how various materials perform in real fire scenarios can be achieved, thereby providing a scientific basis for furniture design. This further emphasizes the importance of considering material properties and combustion dynamics in the design of furniture safety and thermal comfort. Moreover, this method allows designers to optimize material selection and structural design for specific building thermal environment needs.

Table 1. Fitting curve parameters for heat release rate of sofa cushions

Experiment No. Parameter	*SY*-1	*SY*-2	*SY*-3	*SY*-4	*SY*-5	*SY*-6
Reference Peak	117	57	208	458	512	989
Peak Moment	64	81	129	54	54	91
Rising Factor	0.00078	0.00078	0.00078	0.00078	0.00078	0.00078
Falling Factor	0.0125	0.007	0.0124	0.0165	0.0156	0.024
Peaking Factor	1.326	1.425	1.458	1.2	0.9	1.06



(a) Experimental *SY*-1 fitting curve

(b) Experimental *SY*-2 fitting curve

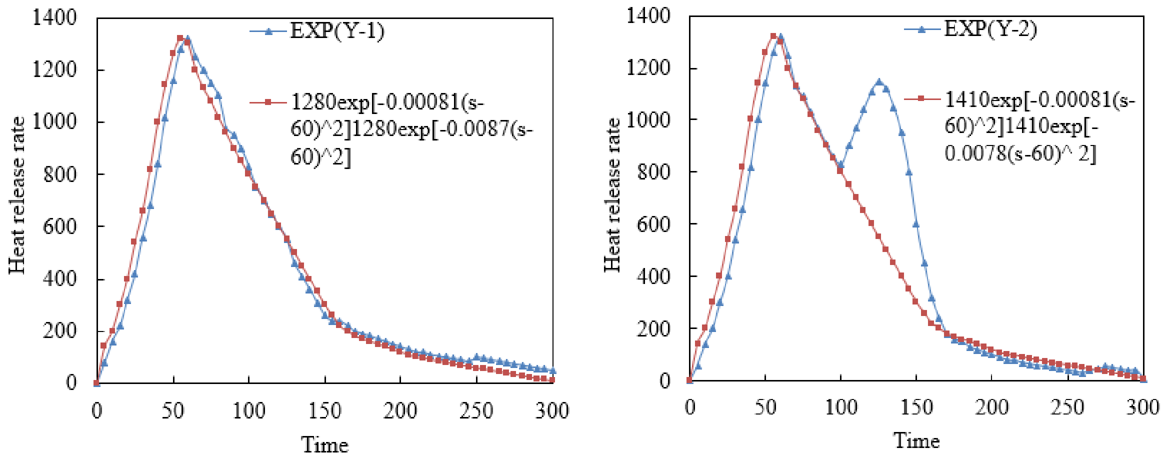
Figure 7. Validation results of the sofa cushion heat release rate prediction model

Table 2. Sofa heat release rate fitting curve parameters table

Parameter Experiment No.	Reference Peak	Peak Moment	Rising Factor	Falling Factor	Peaking Factor
Y-1	1325	61	0.00078	0.0091	0.61
Y-2	1389	84	0.00078	0.0071	0.71
Y-3	1456	84	0.00078	0.012	2.4
Y-4	1985	101	0.00078	0.018	0.514
Y-5	1050	101	0.00078	0.0071	0.1.681
Y-6	1162	114	0.00078	0.013	0.94
Y-7	1265	151	0.00078	0.011	0.041
Y-8	1532	104	0.00078	0.027	2.1
Y-9	1189	111	0.00078	0.0095	0.51
Y-10	1256	81	0.00078	0.012	0.54
Y-11	1423	136	0.00078	0.012	0.71
Y-12	1789	141	0.00078	0.034	2.1

From the validation results of the sofa cushion heat release rate prediction model displayed in Figure 7, the curves for the two datasets (*EXP*(*SY*-1) and *EXP*(*SY*-2)) were fitted and compared using actual experimental data and different mathematical models. In the first dataset, the experimental data showed the changes in heat release rate from the initial phase to 300 seconds, increasing first to a peak and then gradually decreasing. This trend was well captured by two mathematical models (the proposed model and the t^2 model), with the proposed model achieving a higher fitting accuracy, especially around the peak, more precisely reflecting the characteristics of the heat release rate changes. The second dataset also displayed a similar trend of heat release rate changes, with both the proposed model and the t^2 model effectively describing these changes, particularly showing better conformity in fitting data near the peak and during the declining phase. These results indicate that the proposed prediction model can effectively simulate the heat release behavior of sofa cushions under different scenarios, proving the model's broad applicability and accuracy in practical applications. The proposed model is particularly suitable for capturing the peak of the heat release rate and the variations around it. The successful application of this model emphasizes the importance of considering thermal comfort and heat release characteristics in furniture design, especially in improving the quality of the building thermal environment and user comfort.

Table 2 presents detailed data on the fitting curve parameters of the heat release rate for 12 groups of sofas, including reference peak, peak moment, rising factor, falling factor, and peaking factor. The data show that the reference peaks range from 1050 to 1985, illustrating the differences in combustion intensity between different types of sofa materials and designs. All experiments share a rising factor of 0.00078, indicating uniformity in the rate of heat release increase across these tests. The falling factor varies from 0.0071 to 0.034, reflecting significant differences in cooling rates of different sofa materials, while the peaking factor ranges from 0.041 to 2.4, indicating variations in the downward trend after reaching the heat release peak. The peak moment also ranges from 61 seconds to 151 seconds, further revealing the differences in the time it takes for different sofa samples to reach their peak heat release. The analysis results show that by precisely adjusting and setting different curve fitting parameters, this study successfully captures the subtle differences in heat release performance among different sofa samples. This nuanced parameter setting and model application demonstrate the depth and breadth of the research, emphasizing the importance of considering thermal comfort and safety in furniture design.



(a) Experimental *Y*-1 fitting curve (b) Experimental *Y*-2 fitting curve

Figure 8. Validation results of the sofa heat release rate prediction model

From the data shown in Figure 8, the validation results of the sofa heat release rate prediction model for two groups of data (*EXP*(*Y*-1) and *EXP*(*Y*-2)) both exhibit the thermal release characteristics of sofa materials at different time points. In the *EXP*(*Y*-1) data, the experimental values gradually increase to a peak of 1320 at 150 seconds, then gradually decrease. The fitting model demonstrates good performance in the initial and peak phases, especially in accurately predicting near the peak. Similarly, the *EXP*(*Y*-2) data also show a heat release rate that first increases and then decreases, reaching a peak of 1320 at 150 seconds. The model effectively depicts the data changes around the peak and before, although there is a slight deviation in data matching after the peak. The analysis of these experimental results verifies the effectiveness and accuracy of the proposed model in predicting sofa heat release rates. By comparing experimental data and model predictions, it is evident that the model can reliably simulate actual heat release behavior, especially in the critical rising and peak phases. The successful application of this model highlights its practical value in furniture design and building thermal environment assessment, supporting the scientific and practical framework proposed in this paper.

6. CONCLUSION

This study proposes a comprehensive research framework that systematically explores the mutual impact of furniture thermal comfort and the building thermal environment, covering topics such as changes in skin temperature during contact between the human body and furniture materials, the distribution of heat released during the rising segment of furniture, and the fitting and validation of furniture heat release rate models. Through a comprehensive analysis of the thermal transfer properties and combustion behavior of various furniture materials, this paper successfully designs furniture that significantly enhances thermal comfort and scientifically validates these designs.

The results show significant differences in thermal comfort performance between different materials, with fabric and wood being more suitable for furniture designs intended to improve thermal comfort due to their slower temperature changes and good insulation properties. Moreover, by detailed fitting and validation of the heat release rates of sofa cushions and sofas, we find that Gaussian and exponential decay models effectively predict the behavior of furniture during heat release, providing important tools for architects to predict and optimize indoor thermal environments during the design stage. These findings not only deepen our understanding of furniture thermal behavior but also provide a scientific basis for practical applications in furniture design, further advancing improvements in thermal comfort and building energy efficiency.

Despite the achievements of this study, there are still some limitations. For example, the current research is mainly focused on tests under laboratory conditions, and future work could expand to real living environments to verify the applicability and accuracy of the model under broader conditions. Additionally, the environmental adaptability and long-term durability of furniture materials are also directions that future research could further explore. By conducting in-depth studies on these aspects, furniture design can be more comprehensively optimized to achieve the dual goals of thermal comfort and environmental sustainability.

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