A literature review about the numerical model application of heat transfer in buildings

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Abstract. In this paper, we analyze three classical numerical models of heat transfer, including a 1D steady-state model, a 2D transient model and a complex 3D model considering radiative heat transfer. The scope of application, hypothesis, and accuracy of each model were evaluated. To address the heat transfer challenges encountered by structures within the historical urban context, recommendations have been formulated to enhance thermal insulation capabilities. These recommendations encompass the upgrading of materials, reinforcement of insulation layers, and refinement of window designs. Drawing upon the findings and analyses, this paper advances proposals pertinent to the revitalization of ancient cityscapes. This research endeavors to offer both theoretical insights and pragmatic directives, thereby fostering the enhancement of energy efficiency in venerable urban edifices.

Keywords: Numerical Modeling, Heat Transfer, Old Building.

1 Introduction

In the current dynamic landscape of urban development, the pivotal concerns of energy efficiency and inhabitant comfort within buildings have risen to the forefront of architectural discourse. The intricate interplay of heat transfer mechanisms within this context has sparked intense debates among scholars and researchers. Aldeek agreed that the balance between energy conservation and occupant well-being remains a contentious topic [1]. Smithson contended that a singular focus on energy efficiency might inadvertently compromise the thermal comfort of building occupants.

Contrastively, some scholars insisted that prioritizing energy efficiency through advanced heat transfer analyses is the key to achieving both sustainable urban development and occupant comfort, and Johnson's research underscores the significance of numerical simulations in unraveling the intricacies of heat transfer and optimizing thermal performance [2]. By delving into distinct architectural configurations, materials, and design strategies, numerical models, as Johnson asserts, offer an unparalleled vantage point for enhancing energy efficiency while preserving inhabitant comfort [2]. This paper bridges the gap between these seemingly conflicting viewpoints by shedding light on the synthesis of energy efficiency and occupant comfort in buildings located within

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historic urban zones. Through a comprehensive review of prevalent numerical models encompassing heat transfer, with a primary focus on heritage structures, this manuscript aims to uncover the underlying elements and strategies that can be harnessed to augment the effectiveness of heat transfer processes.

2 Numerical Model of Heat Transfer

2.1 Basic principles of numerical models of heat transfer

The heat transfer numerical model is based on the heat conduction equation, which is the basic equation describing the heat transfer inside a substance. The heat conduction equation describes the temperature distribution with respect to time and space. For one-dimensional steady-state heat conduction, the heat conduction equation can be written as:

$$\frac{d}{dx}(k\frac{dT}{dx}) = Q(x) \quad (1)$$

Where k is the thermal conductivity of the material, T is the temperature, and x is the spatial coordinate.

For two or three dimensions, the heat transfer equation becomes:

$$\nabla \cdot (\mathrm{k}\nabla \mathrm{T}) = \mathrm{Q} \quad (2)$$

In numerical simulation, the space is discretized into a grid, and the heat conduction equations are transformed into discrete algebraic equations by finite difference or finite element method. By combining these factors, numerical simulations can more accurately predict the heat transfer process inside buildings, providing a practical tool for optimizing building energy efficiency and indoor environment.

2.2 Application of numerical models in the study of heat transfer

The study of heat transfer processes heavily relies on numerical models, offering a vital avenue for uncovering the underlying mechanisms of heat exchange within buildings. Utilizing numerical simulations, we can progressively deconstruct the micro-level intricacies of heat transfer. This allows us to fathom the nuanced heat flow across diverse materials, architectural forms, and atmospheric circumstances. Furthermore, we delve into the interplay of diverse heat transfer mechanisms such as conduction, convection, and radiation. This meticulous analysis affords us an unparalleled viewpoint for refining energy efficacy and augmenting indoor comfort.

Guided by numerical simulations, we were able to reproduce a variety of complex heat transfer scenarios, simulate the conduction process between different materials, take into account convection caused by indoor and outdoor temperature differences, as well as radiation transfer through the building surface [3]. In addition, numerical simulations allow us to explore heat transfer at different time scales, from steady-state heat transfer to transient heat transfer, giving us a more comprehensive insight.

These simulations are not limited to revealing the temperature distribution inside a substance, but also enable quantitative analysis of energy flows, thereby effectively assessing heat loss and heat gain. By employing numerical simulations, we quantified the building's internal heat loss, furnishing a foundation for decision-making rooted in data [3]. This equips architects, engineers, and decision-makers with a robust instrument to make knowledgeable decisions concerning energy efficiency and indoor comfort during the initial phases of design.

It can be said that numerical simulation is not only a technical means, but also a driving force to promote sustainable building design. By understanding the microscopic processes of heat transfer and incorporating them into design and planning, we can achieve greener and more energy efficient buildings, providing practical solutions for future urban development.

3 Analysis of the Established Numerical Model of Heat Transfer

3.1 Steady-state 1D heat conduction model

Steady state 1D heat conduction model is a basic numerical model used to study one-dimensional Steady state heat conduction. The model is suitable for situations with little spatial variation and no obvious temperature gradient, such as thin-walled structures or long strips. In this model, the temperature distribution remains spatially constant would be regarded as a condition, i.e.. does not change with time.

The model is suitable for relatively simple cases, such as the conduction problem of thin-walled materials, where temperature changes occur primarily in one dimension. However, it cannot handle large temperature changes in space, nor can it capture transient changes [3]. The model ignores the temperature distribution in other dimensions, so it is not suitable for complex three-dimensional structures.

The parameters and assumptions in the model include thermal conductivity. The thermal conductivity was assumed to remain constant through the structure by Dul'Kin & Garas'Ko [4]. Also. it has been assumed that no internal hidden resources, which means there is no boundary resources generated inside the structure. On the other hand, steady state would be another assumption which has been made in this process. So the temperature distribution does not change with time. Ultimately, one-dimensional case is assuming the temperature change mainly occurs in one dimension.

This model usually involves difference approaches, such as finite difference methods. In this approach the space is divided into discrete grid points, and the heat conduction equation is used to discretize the space, and finally the equations representing the temperature distribution are obtained. By solving these equations iteratively, the steady-state temperature distribution can be obtained.

To verify the accuracy of the model, case studies or simulation experiments can be conducted. For example, a standard test problem with known materials and geometric parameters can be simulated to compare the consistency of the simulation results with analytical solutions or experimental data. In addition, the response of the model can be tested by changing parameters such as material properties and boundary conditions [5]. Comparison of simulation results with actual conditions will evaluate the accuracy and applicability of the model.

Although the steady state 1D heat transfer model is limited in scope of application, as the starting point of heat transfer problems, it provides us with a basic framework, which can solve one-dimensional Steady state heat transfer problems in a simple and effective way. However, when dealing with more complex heat transfer situations, more refined models and methods are needed.

3.2 Transient 2D heat transfer model

Transient 2D heat transfer model is a numerical model used to study two-dimensional transient heat transfer problems. Different from the steady-state model, the time factor is considered in this model, which is suitable for analyzing the change of temperature in space and time. This is important in more complex heat transfer situations, such as sudden temperature changes or dynamic heat sources.

This model which was proposed by Belleudy et al. is mainly suitable for problems that require consideration of temperature changes in time and space, such as transient heat sources, periodic changes, or temporary temperature gradients [6]. Compared with the steady-state model, it is more computationally intensive, especially for complex geometric shapes and boundary conditions. In addition, the accuracy of the model can be challenged at short time scales and large temperature changes.

The model is usually solved using the finite difference method or the finite element method. Space is divided into a grid, time is discretized, and heat conduction equations are transformed into discrete algebraic equations. By solving these equations iteratively, the temperature distributions under different time steps can be obtained. Sudden temperature changes can be simulated and then compared with experimental data to assess the model's response. Additionally, Luo and Xu proposed standard test questions can be used for validation to compare the consistency of simulation results with analytic solutions or known data [7].

The Transient 2D heat transfer model has significant advantages in analyzing temporal and spatial temperature changes. While it may add computational complexity when dealing with complex geometry and boundary conditions, it provides us with a powerful tool for understanding and predicting dynamic heat transfer phenomena to guide optimization of building thermal effects and energy efficiency.

3.3 3D heat transfer model of complex building structures

A numerical model known as the three-dimensional (3D) heat transfer model serves to investigate the mechanisms of heat transfer within a tridimensional environment. Lee, Park, and Kim developed when juxtaposed with one-dimensional (1D) and two-dimensional (2D) models, the 3D models exhibit greater intricacy, enabling a more precise emulation of real-world heat conduction in diverse materials and structures, spanning a broader spectrum of scenarios [8]. This model is suitable for heat conduction analysis of various buildings, industrial equipment, and facilities, especially for complex three-dimensional structures or multi-material systems. However, due to the high computational complexity, more computing resources and time may be required. In addition, fine geometric details and large-scale simulations can lead to computational difficulties.

Some researchers used 3D finite element models to study heat conduction and fluid flow in integrated photovoltaic systems in buildings [9], the study considers the interaction of building materials, photovoltaic modules and airflow, and analyzes the temperature distribution and thermal effects in the system through numerical simulation. The research results provide an important reference for optimizing the design and performance of building integrated photovoltaic systems.

3.4 Models that consider radiative heat transfer

A numerical model known as a radiative heat transfer model is employed to delve into the intricacies of heat transfer via radiation. The significance of radiative heat transfer is particularly pronounced within the realms of construction and industrial contexts, especially in scenarios involving elevated temperatures, such as the impact of solar radiation on architectural structures [10]. Unlike the modes of conduction and convection, the radiative heat transfer model encompasses the exchange of energy in the form of electromagnetic waves.

This model finds its niche in scenarios characterized by heightened temperatures and intense energy densities, exemplified by instances like solar radiation and the heat transfer dynamics encountered within high-temperature furnaces. It is especially suitable for scenes with significant surface temperature differences [10]. Different from conduction and convection models, radiative heat transfer models usually require complex radiation characteristic parameters, such as surface emissivity, absorptivity, etc., which are often difficult to determine accurately in practical situations.

Radiative heat transfer in strongly forward scattering media using the Discrete ordinates method is used to simulate radiation heat transfer in glass curtain walls [10]. The radiation characteristics of multilayer transparent materials are considered, and the radiation heat transfer distribution and thermal effect of glass curtain wall under different conditions are analyzed. Through this study, the thermal response of glass curtain walls under solar radiation can be better understood.

The model for radiative heat transfer equips us with a resource for dissecting heat transfer issues under conditions of elevated temperature and energy density. Nevertheless, the constituents within the model exhibit heightened intricacy, necessitating precise parameters that outline radiation characteristics. Furthermore, the intricacy of the model may entail a more intricate solving process. Yet, by harnessing apt numerical methodologies and tools, we can gain a more comprehensive comprehension of the radiative heat transfer mechanism and attain precise outcomes in real-world implementations.

4 Heat Transfer Performance of Buildings in the Old City

Old urban buildings face multiple challenges in terms of heat transfer performance. Initially, it should be noted that the architectural composition and materials of numerous aged constructions might not align with current insulation benchmarks. Significantly, surfaces such as walls, roofs, and floors often lack sufficient insulation, rendering the leakage of heat quite feasible. Moreover, traditional building substances often possess limited thermal conductivity, rendering the mitigation of heat transfer notably challenging. These factors make it difficult for older buildings to maintain a stable indoor temperature, which increases energy consumption and reduces residential comfort.

To solve these challenges, there are several ways to consider: First, choose new materials with better insulation properties, such as insulation bricks, insulation panels, etc., for walls and roofs. This helps to reduce heat transfer and improve the thermal effect of the building. Second, adding insulation to the surface of the old building can not only improve the thermal insulation performance, but also protect the historical structure. Technologies such as external insulation systems (ETICS) can effectively improve the insulation effect. Third, Windows are one of the main ways of heat transfer. By using double Windows, airtight window frames, and low-radiation coated glass, heat transfer in the window area can be reduced. In addition, the thermal bridge phenomenon common in older buildings can cause local temperature differences and reduce indoor comfort. Through structural design and insulation measures, the thermal bridge effect is reduced.

5 Discussion

The Steady state 1D Heat Conduction Model is suitable for those cases where heat conduction is present in only one direction, thus simplifying the mathematical and computational complexity [4]. Because the direction of heat conduction is limited, the calculation speed of the model is relatively fast, and the thermal equilibrium state of the system can be analyzed quickly. For beginners, the one-dimensional model is easier to understand and apply, and is an introductory model for heat conduction problems. However, for some practical situations, the results may be inaccurate by ignoring heat transfer in other directions. The Transient 2D Heat Transfer Model can more accurately simulate the actual heat transfer process, taking into account heat transfer in multiple directions [7]. The time change process of heat conduction can be analyzed, which is more suitable for problems with short time scales or significant changes. Nonetheless, the formulation and computation of a two-dimensional model exhibit a higher level of complexity compared to a one-dimensional counterpart, necessitating a greater allocation of mathematical and computational resources. The transient two-dimensional heat transfer model finds its applicability in scenarios demanding the incorporation of multi-directional heat transfer, intricate geometrical configurations, and significant temporal fluctuations. For example, heat dissipation analysis of electronic components, temperature distribution inside buildings, etc. Overall, the choice of the appropriate heat transfer model depends on the complexity and requirements of the specific problem.

When improving the thermal insulation performance of buildings in the old city, it is necessary to balance the relationship between sustainable development and cultural heritage protection. Improvement measures need to respect the uniqueness and character of the historic building. At the same time, the impact of new materials and technologies on the appearance and structure of buildings should also be considered to ensure the protection of cultural heritage.

While improving heat transfer performance, sustainability principles, such as energy saving, emission reduction, resource utilization, etc. need to be followed to ensure that the improvement not only meets modern requirements but also does not have a negative impact on the environment. By striking a balance in improving the heat transfer performance of buildings in the old city, sustainable development goals can be achieved and valuable cultural heritage preserved.

6 Conclusion

In the field of construction, heat transfer performance is an important factor affecting energy efficiency, indoor comfort, and environmental sustainability. By analyzing different types of numerical models of heat transfer, including 1D steady-state models, 2D transient models, and 3D models that take into account radiative heat transfer, this paper explores in depth the role of these models in understanding and optimizing heat transfer processes. At the same time, in view of the challenge of heat transfer performance of buildings in the old city, we discussed the methods to improve the thermal insulation performance, such as improving materials, increasing insulation, optimizing window design, etc. By studying and applying heat transfer models, we are able to better understand the energy transfer mechanisms inside buildings and provide guidance to designers and engineers to create more energy-efficient, environmentally friendly, and comfortable built environments. While pursuing technological innovation, we must keep in mind the principles of sustainable development and integrate environmental protection into building design and improvement.

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