Progress in the Application of Multi-Scale Simulation Technology in the Study of Building Environment Comfort

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Abstract. Against the backdrop of climate change and urbanization, issues such as energy consumption and public health are becoming increasingly prominent. The building environment comfort is crucial for the physical and mental health of residents. Multi-scale simulation is a cross-scale analysis tool. It is able to evaluate environmental comfort at multiple levels, including city simulation, zone simulation, building simulation, and indoor simulation, and provide data support for design optimization. This paper reviews the advancements in the application of multi-scale simulation technology in building environment comfort, covering its theoretical foundations (such as computational fluid dynamics and computational thermal dynamics), technical framework, and typical cases. Research indicates that multi-scale simulation technology has proven effective in mitigating urban heat island phenomenon, optimizing street form, and enhancing both thermal and visual comfort in buildings. However, current research still faces challenges such as high computational resource consumption and insufficient integration of multiple factors. Future efforts should focus on establishing systematic comfort evaluation standards and promoting interdisciplinary integration (such as artificial intelligence and materials science) to achieve more precise and efficient optimization of the building environment.

Keywords: Multi-scale Simulation, Building environment, human comfort.

1. Introduction

The comfort of building environment plays a critical role in residents' physical and mental health in their lives. With the rapid progression of global warming and urbanization, the issue of building comfort has gained increasing prominence, particularly in urban settings where it is intricately linked to urban climate change, energy consumption, and public health. Multi-scale simulation technology, as a cutting-edge analytical tool, enables the evaluation of building comfort across various scales—such as the building, indoor, and urban levels—and offers critical data support for the design and optimization of building environments.

Building environment comfort refers to- subjective feelings of occupants about their physical and mental state in or around the building. Indoor environment comfort is primarily influenced by air quality, light intensity, temperature and humidity conditions, and noise levels. Meanwhile, outdoor environment comfort is influenced by natural conditions and socio-cultural factors. Temperature and humidity directly affect human thermal exchange. High humidity exacerbates the feeling of stuffiness, while low humidity causes dryness and discomfort. Lack of natural light can lead to low mood and even depression, while improperly designed artificial lights can lead to visual fatigue. Poor ventilation leads to increased carbon dioxide concentrations and the accumulation of pollutants, affecting lung health. If someone who exposed in noisy environments (e.g., traffic, equipment noise) for a long-tern can cause insomnia and cardiovascular disease. Therefore, these building comfort factors have a significant impact on human health and the overall well-being of the residence. Multi-scale simulation technology can analyze the impact of these factors on human comfort in detail and give suggestions for improving terrible conditions. Multi-scale simulation technology is a technology that discusses the simulation methods and basic theories of the building environment from the perspectives of different scales (urban scale, building scale, building internal scale, etc.). This approach simplifies complex environmental systems, enhancing computational efficiency. For instance, Yu-han Wang and Cheng Qian from Qingdao University of Technology conducted a study on a residential community in Xi'an, employing Computational Fluid Dynamics (CFD)-based Thsware VENT2014 software to simulate the impact of outdoor wind speed around high-rise buildings on human wind comfort. In this study, the shape, size, spacing, and topography of the building were added to the effect of wind speed to obtain the optimal outdoor wind speed for the human body. This is very valuable for real-world architectural design [1]. Similarly, CFD simulations have been used to more accurately assess the thermal comfort of offices under different ventilation modes. And the studies of H Kabrein, A Hariri, A M Leman, M Z M Yusof and Afandi have concluded that the effects of different modes of air supply systems in office thermal comfort are very different. Mixed ventilation is better at improving thermal comfort [2]. This study helped with the air conditioning setup in office.

Nevertheless, multi-scale simulation technology confronts persistent challenges. Although the computational efficiency of simulation technology has improved, large-scale simulations still require a lot of computational resources. Most current simulation technologies only aim at a certain comfort level of the building, such as building thermal environment comfort, building ventilation environment comfort, building noise environment comfort, etc. The comfort levels of these classifications are not integrated into a complete system. For instance, Gross Guenter's microscale ASMUS (Ausbreitungs- und StrömungsModell für Urbane Strukturen) model successfully linked pedestrian wind comfort with airflow patterns [3]. However, it is not combined with other comfort factors such as temperature and noise, to give an overall comfort level. Therefore, in the future, a systematic evaluation standard for building comfort is needed, including temperature, humidity, noise, etc., to form an overall evaluation system for building comfort. The application of multi-scale simulation technology in architecture also needs to be interdiscursively studied, such as artificial intelligence, materials science, and meteorology. Artificial intelligence can intelligently analyze the building environment comfort and give accurate suggestions. Meteorological architecture can be used to simulate the air flow and precipitation conditions more realistically.

2. Organization of the Text

Multi-scale simulation technology is the use of computer simulation technology to simulate the building environment from different scale levels (such as urban scale, regional scale, building scale). This technology divides the environmental system into different scales, such as macro, meso, and micro, each with its own mathematical model. The cross-scale coupling mechanism facilitates the flow and exchange of data across these different levels. This multi-scale approach allows for a comprehensive and precise simulation of environmental phenomena, providing strong support for optimizing designs, particularly in complex urban and architectural environments. The multi-scale simulation technology establishes the corresponding mathematical model by dividing the system into macro, micro and other scale levels. And it realizes data interaction through the cross-scale coupling mechanism. Through the division of the system into different scales (macro, meso, micro), the technology establishes tailored mathematical models at each scale level. The data is then exchanged and coupled across these levels, which ensures more accurate and comprehensive environmental simulations. This method is particularly useful for simulating complex building environments. Through the cross-scale coupling mechanism, this technology facilitates data interaction between different levels, improving both computational efficiency and accuracy. This approach optimizes resource allocation by reducing the complexity of calculations at each scale. Additionally, it enhances prediction accuracy by coupling multiple factors, such as temperature, airflow, and material properties. In the building environment, the technology can be compared to the collaborative simulation of three scales: urban scale, regional scale, and building scale. Liu Xiang in Jiangsu University used the climate of Jiangsu Province as a template to establish an architectural model of urban communities. He analyzed the optimization of the outdoor wind environment of the community from four aspects: urban scale, community scale, building scale and green plant scale. Combined with the results of the optimization analysis with the real residential community called Hongjunxian, the optimization layout of the community is proposed [4]. Therefore, multi-scale simulation technology is of great help to the rational layout of buildings.

Multiscale simulation technology does help with building design and optimization by simplifying complex environmental systems. Meanwhile it can improve computational efficiency. This technique reduces the computational complexity of a single scale through hierarchical modeling. In the simulation of the building environment, the macro climate model can provide boundary conditions, and the micro indoor model refines the local thermal environment to avoid the resource consumption of direct calculation at full scale. In addition, the multi-scale simulation technology uses the decoupling and parallel computing technology between multiple scales to optimize the resource allocation. Prediction accuracy can also be improved through multi-factor coupling analysis (e.g., temperature, airflow, material properties). Therefore, multi-scale simulation technology can comprehensively analyze environmental factors at different scales to obtain a more accurate environment comfort assessment.

A variety of basic theories such as computational fluid dynamics (CFD), computational thermal dynamics (CTD), and finite element analysis (FEA) are used in multi-scale simulations. Researcher use some computer software to calculate and simulate buildings such as: Yuying Liang, Huijun Wu, Jianming Yang, Gongsheng Huang. They used ANSYS Fluent for steady-state simulations. They used an achievable K-ε turbulence model to deal with near-wall treatment and full buoyancy effects. A coupling algorithm is used to model the relationship between pressure and velocity of the airflow in the fluid region. During the CFD simulation, they meshed the human body to turn it into a three-dimensional mesh to ensure the accuracy of the CFD simulation model [5].

3. Literature References

In the city-scale simulation, Jiacheng Huang, Zhengdong Huang, and Wen Li generated micro-climate data (including air temperature, relative humidity, and wind speed) in Shenzhen by combining the WRF model and the numerical simulation of the LCZ (local climate zone) scheme. They imported the LCZ topographic map of Shenzhen into the model and calculated the net effective temperature (NET). Finally, they obtained the overall thermal comfort level of the built-up areas in Shenzhen. The study showed that the built-up areas in the northeast and southwest of Shenzhen have poor thermal comfort during the summer rainy season, which is a warning for future urban building settings in Shenzhen [6].

Feifei Dong and Takashi Asawa took Building No. R1-A in the Suzukakedai campus of Tokyo Institute of Technology and its surroundings as the subject of their research. This area, located on the border of Yokohama City and Tokyo, Japan, has a humid subtropical (Cfa) climate. Their study focused on individual urban modules, grouping building layouts by construction locations. The research considered ground cover and vegetation cover strategies in the outdoor environment. It also focused strategies for optimizing windows, building envelopes, and air conditioning systems. The SEB model elucidates the combined effects of various commonly used building layouts. And it reduces building energy consumption in both summer and winter. They simulated 110 buildings in the urban area of Yokohama, Japan by using the SEB model. The study found that sensible heat emissions were higher during summer, while the energy consumption of buildings was higher during winter in the study area. Reducing air conditioning energy can effectively lower the overall building energy consumption in Yokohama, thus alleviating the urban heat island (UHI) phenomenon. Changing ground cover, adjusting the building's roof coverage, and planting trees are effective in mitigating the UHI phenomenon. Planting large deciduous trees is the most effective method. To test effective strategies for mitigating the urban heat island phenomenon, they applied various strategies and combined them [7].

Ultimately, they concluded that interactions between multiple strategies could enhance or offset their benefits. When multiple strategies are implemented simultaneously, Architectural designers should carefully consider their negative offsetting effects and additional benefits. This presents a practical operational plan for effectively alleviating the urban heat island phenomenon.

Shivanjali Mohite and Meenal Surawar conducted a regional-scale study on explore the impact of urban street morphology on pedestrian thermal comfort. They used Nagpur, Maharashtra, India as the research object. The researchers selected four typical streets to collect micr-climate data at specific times of the day. And they combined the data with ArcGIS software to construct a physical model of the streets. They simulated the mean radiation temperature (MRT) and modified physiological equivalent temperature (mPET) thermal comfort metrics by using RayMan Pro software. It was found that the mPET index was significantly correlated with the micro-climate parameters, which affected the overall thermal experience of the human body. Their research emphasizes the key regulatory role of geometric parameters such as street height-to-width ratio and sky sightshed on thermal comfort. They pointed out that streets with different orientations and width-to-narrow ratios will form different thermal stress distribution patterns. They suggested that improving the street canopy cover in built-up areas could effectively improve thermal comfort. In the planning of new districts, the quality of the thermal environment can be improved by optimizing the street form [8].

Their research innovatively proposes a bottom-up paradigm for street design. It emphasizes that the optimization of thermal comfort is the core of pedestrian space design. It provides a quantitative decision-making basis for the construction of urban streets. The research results not only deepen the understanding of the mechanism of pedestrian heat exposure in tropical cities, but also provide an operational technical path to improve pedestrian friendliness. Therefore, it has reference value for the street design of cities in similar climate zones around the world.

At the building scale, Mohammadreza Baghoolizadeh, Mohammad Rostamzadeh-Renani, Reza Rostamzadeh-Renani, and Davood Toghraie selected a room on the middle floor of a 24-hour office building in Tehran, Iran to study the effect of blinds on improving the thermal comfort and visual comfort of building occupants, they used JEPLUS software for parametric analysis, covering 21 parameters of the blinds. Sensitivity analysis (Morri's method) and multi-objective optimization (NSGA-II algorithm) are implemented by JEPLUS EA. Finally, it is concluded that the performance of the external blinds is better than that of the internal blinds. Because the visual comfort and thermal comfort for external blinds are higher. Moreover, the conclusions have the value of being extended to other climate zones, providing a reference for building energy conservation and humanized design [9].

Zhengshu Chen, Yanqiu Cui, Haichao Zheng, Qiao NingIn ordered to effectively evaluate and optimize the environment comfort of the atrium in teaching building, a model based on NSGA-II and LGBM algorithms was constructed. They took two atriums of a university teaching building in Jinan as an example. They conducted on-site research and testing in the atrium of the university to obtain environmental data from the atrium. They used the Grasshopper (Ladybug Tools) platform to build a solar thermal performance model and an energy model of the atrium. They found that the design by using NSGA-II and LGBM algorithms can effectively generate a comfortable atrium design scheme [10]. This research provides an optimal reference for designers. The use of multiscale simulation allows designers to evaluate designs more efficiently and accurately.

4. Conclusion

Multi-scale simulation technology provides an important means for the evaluation and optimization of building environment comfort through multi-scale data coupling and computer data modeling. In terms of city-scale simulation, the technology combines meteorological models and local climate zoning to reveal the relationship between human thermal comfort, visual comfort, wind environment comfort and the building environment. It is proposed that strategies such as vegetation coverage and building optimization layout can effectively alleviate the negative effects on human comfort, such as urban heat island phenomenon. In terms of regional-scale simulation, by simulating the local environment of an area, the types of regional architectural designs that affect human comfort can be obtained. This allows architects to optimize community design while taking into account microclimate data and spatial morphology. At the building scale, the indoor ventilation environment and light environment are simulated to verify the effectiveness of multi-scheme optimization in improving human comfort and energy saving potential.

To sum up, multi-scale simulation technology has great reference significance for specific cases in architectural design and building environment optimization. However, there are still limitations to the current technology: large-scale simulation is highly dependent on computing resources, and further combination of computing and optimization algorithms is needed to improve efficiency; Second, the existing studies mostly focus on a single comfort index (such as thermal environment or wind environment) and lack the collaborative analysis of multiple factors such as humidity and noise.

The future development of multi-scale simulation technology lies in constructing a comprehensive comfort evaluation system that encompasses multiple environmental parameters, while further deepening interdisciplinary integration—for example, leveraging machine learning to intelligently interpret simulation data. Through continuous technological innovation and cross-domain collaboration, this approach is expected to offer more holistic and effective decision support for the design of human living environments.

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