学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Design and control optimization of an open-type radiant ceiling panel system for thermal comfort and energy saving
(オープンタイプ凹型天井放射パネルシステムの設計と制御の最適化に関する研究)

Buildings are responsible for a significant portion of global energy consumption, accounting for approximately 34% of the total energy use. There is a pressing need to reduce energy consumption in the building sector. The radiant ceiling panel (RCP) system is an energy-efficient alternative to conventional heating and cooling systems. The open-type RCP system is defined as the radiant panels suspended from the ceiling with an open area above the panels. This system enables the use of higher inlet water temperatures in summer and lower inlet water temperatures in winter to prevent surface condensation and ensure the efficient operation of the integrated energy system. Nevertheless, the open-type RCP system still faces practical challenges such as adverse effects from solar radiation through windows, long response time, and lack of knowledge regarding efficient operation settings. A novel open-type RCP with curved and segmented structure was proposed to enhance the convective heat transfer, aiming to improve the system efficiency. The main targets of this thesis are to (1) verify the thermal performance of this novel RCP system under different operating conditions, (2) optimize the design of this novel RCP system to improve the cooling capacity and reduce the effect from building envelopes, and (3) optimize the operation of this novel RCP system in terms of both thermal comfort and energy saving.

In this thesis, Chapter 1 serves as an introduction that outlines the research background, describes the motivation and objective of this study, and presents the thesis structure. Chapter 2 provides a detailed description of the radiant ceiling panel system and an overview of the research hotspots in this area. The optimization of the RCP system is reviewed, covering aspects of panel structure and arrangement, integrated system design, and control strategies. In addition, a novel open-type RCP system is introduced, and the optimization methods used in this thesis are also presented.

In Chapter 3, a series of laboratory experiments were conducted under different operating conditions to investigate the cooling performance of the novel RCP system. The results indicate that the curved and segmented structure enhances both radiation and convection, especially the convective heat transfer coefficient obtained with this panel was larger than other panel types. Subsequently, a field study was conducted in an office building to investigate this novel RCP system for one year. The experimental measurement illustrates that the application of the novel RCP system can achieve a comfortable indoor thermal environment. More than 70% of the staff selected the neutral level in the thermal sensation votes (TSV). Moreover, the energy performance of the integrated RCP and groundwater heat pump (GWHP) system was investigated, and the intermittent and continuous operation methods were compared during winter. Compared with intermittent operation, continuous operation could improve both the system performance and indoor thermal comfort.

In Chapter 4, a three-dimensional CFD simulation model was developed to simulate the thermal process of the novel RCP system used in an enclosed space and validated with the measurements provided in laboratory experiments. Firstly, the panel shape was optimized to maximize the cooling capacity. Panel structure was determined based on six design parameters. The sensitivity analysis was then conducted based on the simulations and concluded that void distance plays the most crucial role in influencing cooling performance. Secondly, an integrated novel open-type RCP with wall-attached ventilation (WAV) system was proposed to prevent the warm air stream that floats from the window. The result indicated that applying the ventilation system with the ceiling outlet is more effective than

the floor outlet. After that, the surface response and sensitivity analysis of the operating condition are carried out to optimize the integrated system.

In Chapter 5, a simplified thermal resistance and capacity (RC) network model was developed for the open-type RCP system. The model was validated using measurements from the field study. The results demonstrate that the model accurately predicts indoor thermal conditions, and parameter identification by the Least-Square Method (LSM) is effective for this system. The system operation was then improved by multi-objective optimization based on the RC-network model. The issues encountered during operation, such as the temperature not reaching the target in the morning due to the long response time, were resolved. In addition, the life cycle cost was calculated to show the benefits of optimization.

In Chapter 6, a summary of the key findings of this research is concluded and potential future research directions are outlined.

In summary, this study has demonstrated that the novel RCP system with curved and segmented structure can improve heat transfer efficiency. The novel RCP is optimized to achieve better indoor thermal conditions, energy savings, and cost reduction through advanced methodologies. It is believed that this research will contribute to the widespread adoption of the radiant ceiling panel system. Furthermore, the results of this thesis have significant practical implications for reducing building energy consumption while maintaining indoor thermal comfort and moving toward a zero-emission society in the future.