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A Study on The Three-Dimensional Temperature and Velocity Fields of Natural Convection Heating Systems for Mobile Home

Hyun-Woo Won, Yong-Gy Chae and Dong-Hyun Cho*

Department of Mechanical Engineering, Daejin University, South Korea

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ABSTRACT
This study explores the use of natural convection heating in mobile homes by embedding panels in the walls that utilize hot water to supply thermal energy. It implemented natural convection heating with the thermal energy supplied by hot water by embedding natural convection panels in the walls of a natural convection heating system for mobile homes. The size of the natural convection heating system for mobile homes is 1800 mm wide, 1100 mm long, and 2100 mm high. The results of three-dimensional temperature and velocity fields inside the mobile home in this study showed uniform three-dimensional temperature and velocity fields resulting from the natural convection heat transfer inside the mobile home, and the temperature fields were shown to be well-being temperature fields beneficial to health. It was verified that heating is achieved by natural convection heat transfer, which is beneficial to health. In mobile home heating, the experimental natural convection heat transfer value and the theoretical natural convection heat transfer value of the air for heating matched relatively well in the entire range of the experiment. In addition, as the mass flow rate of hot water increased, the air temperature inside the mobile home rose. Therefore, as the hot water flow rate increased, the heating performance of the mobile home improved.

Keywords: Mobile Home, Natural Convection, Temperature Field, Velocity Field, Three-Dimensional Field

1. INTRODUCTION

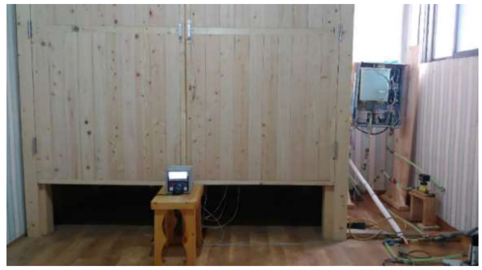
The issue of energy saving has been discussed for years with environmental problems, since the 1973 oil crisis brought energy issues to the forefront (Kim et al., 2019; YJ et al., 2012; Steeman et al., 2010; Porwal, 2024; Bagga et al., 2024; Kim & AlZubi, 2024). The energy reliant on foreign in many countries comes to a high percentage, and a significant portion is occupied house heating in terms of energy consumption (Mendes et al., 2003; Woods et al., 2013; Hai & Duong, 2024). To reduce energy consumption in the house part, energy-saving heating systems are required in the heating system (Barbosa & Mendes, 2008; Cappelletti et al., 2011). A house's heating types are divided into floor and radiator heat types (Sap, 2014; Park & Kim, 2012). Generally, Western house heating uses conventional heat from the radiator, and some Asian countries, including Korea, use floor heating (DoE, 2010). The floor heating mechanism is that the heating sources, such as boiled water or fire, heat the floor first, and the heated floor increases the house's temperature (Hyun et al., 2014). Generally, the house has at least two more rooms, and they are also connected by connecting pipes to transfer hot water or steam to heating rooms (Anitha & Vidyaraj, 2019). To heat a whole house, the individual rooms are heated in an order that makes the temperature of each room different from the others (Bhattacharjee et al., 2020). It can be a major energy loss of house heating system. As demand for mobile homes is gradually increasing, studies on heating device technologies suitable for mobile homes are desperately required. However, reports of the results of such studies still need to be more (De & Datta, 2019; Tyagi & Mishra, 2019). Therefore, in this study the bed and walls were constructed with natural convection panels to implement natural convection heat room heating thereby developing a well-being heating technology beneficial to health. In addition, the existing heating of a mobile home heated the entire room, but in this study, a technology that can only heat the bed space was developed reduce the natural convection heating energy consumption rate greatly. With increasing energy costs and growing environmental concerns, the need for efficient heating systems in mobile homes has become critical. Current heating solutions often fail to provide uniform heating and lack the necessary efficiency, leading to discomfort and higher energy consumption. This study aims to address these issues by developing a natural convection heating system that not only ensures uniform heating but also offers health benefits through improved air circulation and temperature distribution. By embedding natural convection panels within the walls of the heating system, we explore the potential for creating a more effective and sustainable heating solution for mobile homes.

2. EXPERIMENTAL APPARATUS AND METHOD FOR MOBILE HOME

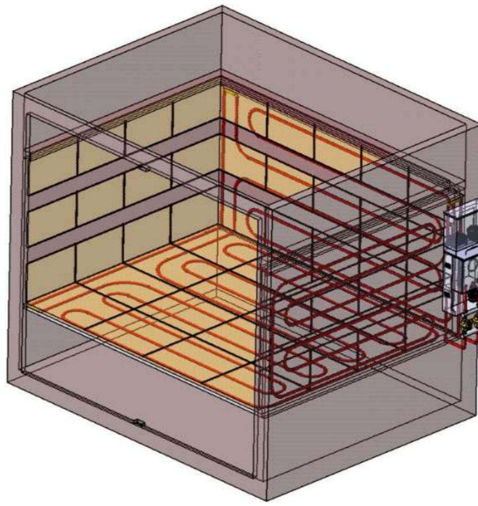
This study utilized a comprehensive experimental setup to investigate the effectiveness of a natural convection heating system for mobile homes. The heating system, measuring 1800 mm in width, 1100 mm in length, and 2100 mm in height, was equipped with embedded natural convection panels within the walls. Hot water circulated through these panels, providing the thermal energy required for heating. Temperature and velocity fields within the mobile home were measured using calibrated thermocouples and anemometers strategically placed at various locations to capture three-dimensional data. The hot water flow rate was controlled and varied to observe its effect on the air temperature and heating performance. Data collection involved continuous monitoring over set intervals, ensuring comprehensive coverage of the heating dynamics. The collected data were analyzed using computational tools to generate detailed temperature and velocity field distributions. Statistical methods were employed to compare experimental natural convection heat transfer values with theoretical predictions. Diagrams and schematics of the experimental setup and sensor placements were created to enhance clarity and facilitate replication of the study. This detailed methodological approach ensured accurate assessment of the natural convection heating system's performance, focusing on its efficiency and health benefits.

2.1 Experimental apparatus for mobile home

Fig. 1 shows an experimental apparatus for a natural convection heating system for a mobile home in which the heating energy held by hot water circulating in natural convection panels embedded in the walls of the mobile home is supplied to the air inside the mobile home for heating. Fig. 2 shows a three-dimensional schematic diagram of the mobile home experimental apparatus in which the heating energy held by hot water circulating in the natural convection panels embedded in the mobile home's walls is supplied to the air inside the mobile home for heating. As shown in Fig. 1 and Fig. 2, for the first time at home and abroad, this study examined natural convection heating with the heating energy supplied from hot water by embedding natural convection panels in the walls of a mobile home and installing hot water tubes inside the natural convection panels. The size of the mobile home is 1800 mm wide, 1100 mm long, and 2100 mm high. The size of the mobile home was determined to be the same as that of a single bed. A mobile home of the same size as a single bed was studied to be used as a bed at normal times and used for a dry sauna by those who like dry saunas in their own house where they live. In addition, the heating area of the mobile home experimental apparatus is 0.6 m2 and an experimental study and analysis of three-dimensional temperature and velocity fields of natural convection heating system for mobile home was conducted to implement well-being heating beneficial to health by supplying natural convection heat from hot water by embedding natural convection panels in the bed and walls and configuring the natural convection panels so that hot water is circulated in them. The experimental study and analysis of three-dimensional temperature and velocity fields were carried out so that a residential life with a bed and a loess dry sauna room can be implemented simultaneously by constructing a loess bed and loess walls. The bed and walls were constructed with natural convection panels to implement natural convection heat room heating, thereby developing a well-being heating technology that benefits health. In winter, the hot water's temperature and velocity fields circulating in the bed's natural convection panels and walls can be raised and adjusted so that a natural convection heat dry sauna can be enjoyed in the bed space, depending on the resident's taste. In spring and autumn, the ceiling of the mobile home with a bed that can also be used as a natural convection sauna room can be placed at the height of the room's ceiling; the wall can be placed in close contact with the room's wall. As a result of this study, well-being heating, which is comfortable and beneficial to health, was implemented because natural convection heating is implemented without movement or circulation of air, unlike forced convection heating, in which air is circulated by force with an air conditioner. This study employs a comprehensive three-dimensional analysis of temperature and velocity fields within the mobile home. This approacmeasurement techniqueh provides a detailed understanding of how natural convection heat transfer occurs and distributes heat uniformly, which is not commonly addressed in existing research.



[**Fig. 1**] An experimental apparatus for a natural convection heating system for mobile home



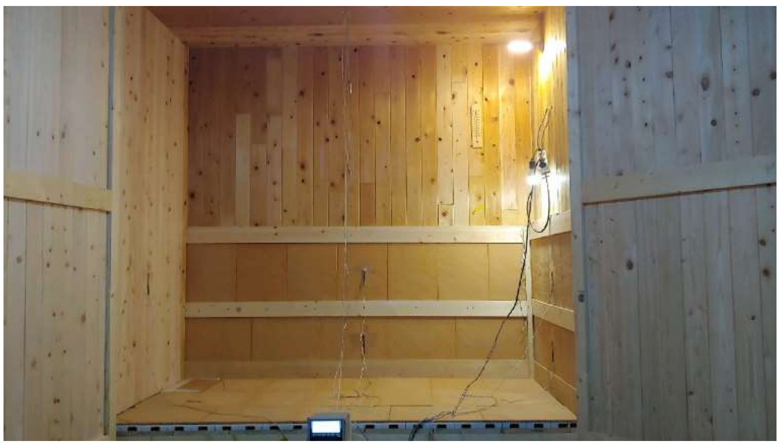
[**Fig. 2**] Three-dimensional schematic diagram of the natural convection heating system for mobile home

Fig. 3 shows an integrated water bath boiler supplying hot water heating energy to the mobile home. As shown in Fig. 3, an integrated water bath boiler for supplying hot water heat to the natural convection panels of a mobile home was installed to conduct an experimental study. The noise of the integrated water bath boiler for hot water heat supply was limited to 38 dB, so there was no sleep disturbance due to noise when a person was sleeping in the mobile home at night. Since an integrated water bath boiler and the technology were developed as such, the energy loss could be reduced by 3% compared to the existing technology for installing the boiler outdoors when considering the heat dissipation loss and the loss of heat in the pipe.

[**Fig. 3**] Integrated water bath boiler for supplying hot water heat to mobile home

2.2 Measurement of the temperature and velocity field of the air inside the mobile home and the walls and the hot water flow rate

Fig. 4 shows a temperature sensor to measure a mobile home's air temperature and wall temperature. The wall temperatures of the mobile home were measured by attaching three Pt 100 temperature sensors, one each on the upper, middle, and lower areas of the right wall and the center wall of the mobile home, respectively. In addition, the floor surface temperatures were measured by attaching three Pt 100 temperature sensors at equal intervals on the left and right sides of the floor of the mobile home, respectively. Furthermore, three Pt 100 temperature sensors were installed at equal intervals, one each on the upper, middle, and lower areas of the mobile home to measure the air temperatures, and Pt 100 temperature sensors were installed at the inlets and outlets of the natural convection panels embedded in the walls and floor of the mobile home to measure the hot water temperatures at the inlets and outlets. Fig. 5 shows the flow meter system for the hot water flowing in the natural convection panels inside the mobile home. As shown in 5, a flow meter system was installed on the hot water tube at the entrance of the mobile home to measure the hot water flow rate.



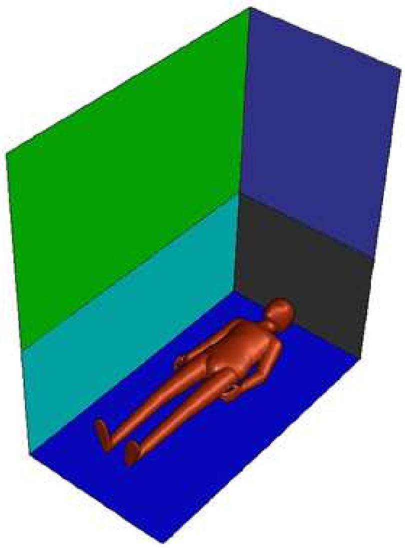
[**Fig. 4**] Experimental apparatus in the temperature fields for mobile home

[**Fig. 5**] Experimental apparatus in the flow velocity fields for mobile home

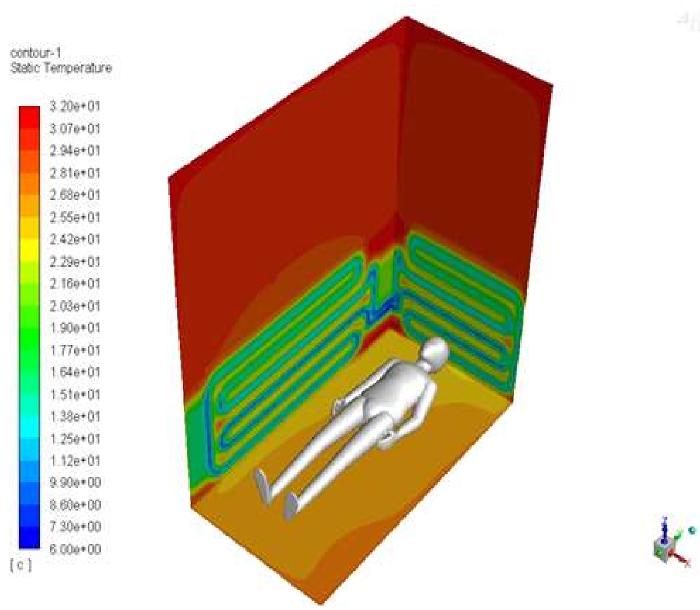
3. RESULTS

3.1 The three-dimensional temperature and velocity fields of natural convection heating system for mobile home

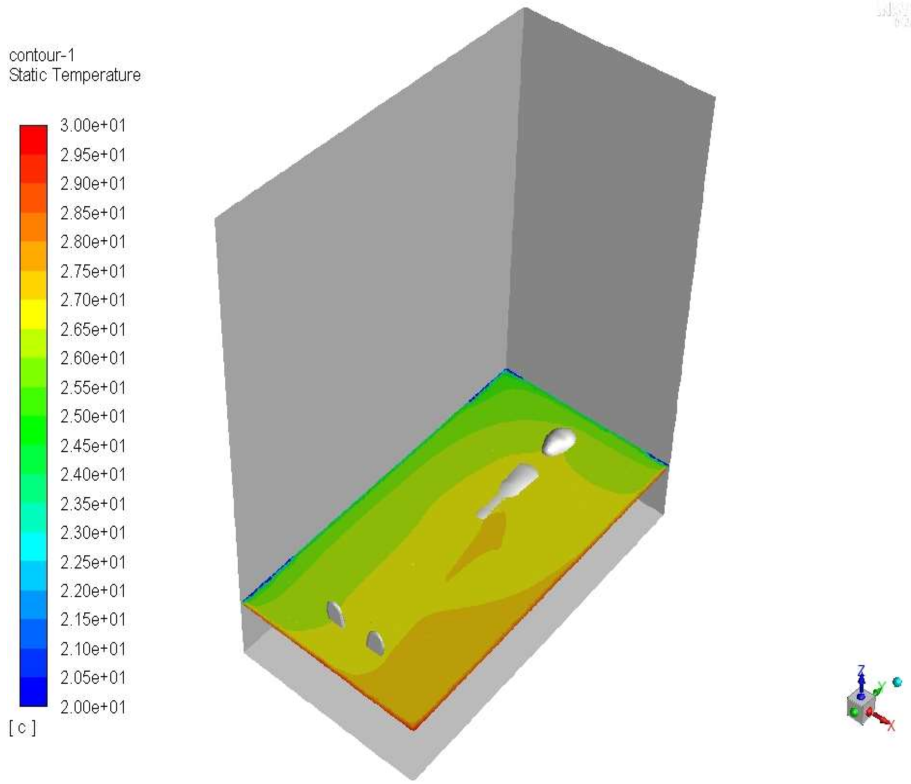
Fig. 6 to Fig. 10 show the analysis results of the three-dimensional surface temperature fields of the wall and floor inside the mobile home and the three-dimensional air temperature fields and three-dimensional airflow velocities in the space inside the mobile home. The size of the mobile home is 1,800mm wide, 1,100mm long, and 2,100mm high. As shown in Fig. 6, three-dimensional temperature and velocity fields were studied at 80°C of the hot water flowing into the inlets of the natural convection panels embedded in the walls and floor inside the mobile home. In addition, three-dimensional temperature and velocity fields were studied under the conditions of a flow rate of hot water of 3.2 L/min and an outdoor temperature of 35°C. ANSYS FLUENT R19 was used as the analysis software. The natural convection heat transfer inside the mobile home was simulated with gravity and incompressible ideal gas air. From the results of study of the three-dimensional temperature field of the air inside the mobile home in Fig. 7 to Fig. 9, the average three-dimensional temperature fields of the air inside the mobile home was found to be 27°C, the three-dimensional air temperature fields at a height of 500 mm from the base of the mobile home was found to be 26° C and the three-dimensional air temperature fields at a height of 1,000 mm from the base of the mobile home was found to be 27°C. From the results of study of the three-dimensional air temperature fields, the three-dimensional air temperature fields resulting from natural convection heat transfer inside the mobile home were found to be uniform and considered well-being temperature fields beneficial to health. In addition, in this study, the three-dimensional air temperature field measured in the experimental study and the three-dimensional temperature fields value shown in the study results were in good agreement. Fig. 10 shows the airflow velocities fields in the mobile home's central cross-section. The results of the analysis of the three-dimensional airflow velocity fields show 0.01~0.02 m/s. From the results of analysis in this study, the fields of airflow velocity were found to be much lower than that of the heating system by forced convective heat transfer, which is the conventio nal heating method. Therefore, from the results of the study for three-dimensional temperature and velocity fields of natural convection heating systems for mobile homes in this study, it was verified that the heating of mobile homes is achieved by natural convection heat transfer, which is beneficial to health.



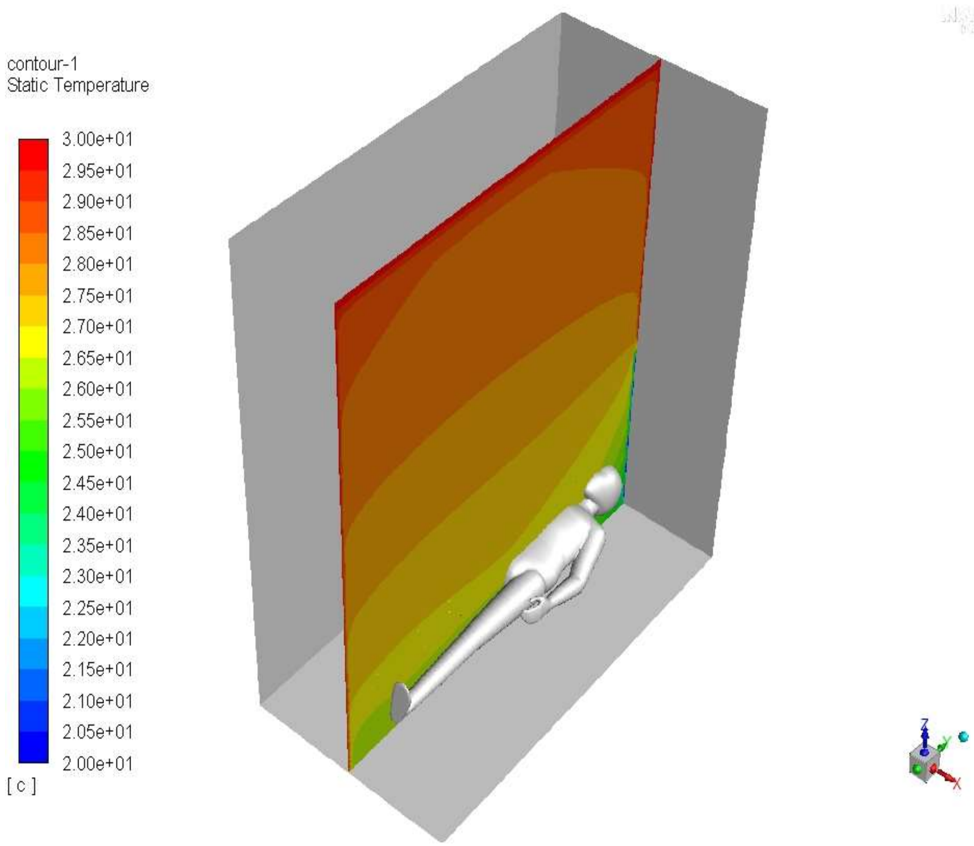
[**Fig. 6**] Shapes of simulations of three-dimensional surface temperature fields of the walls and floor inside the mobile home, internal air temperature field and airflow velocity fields



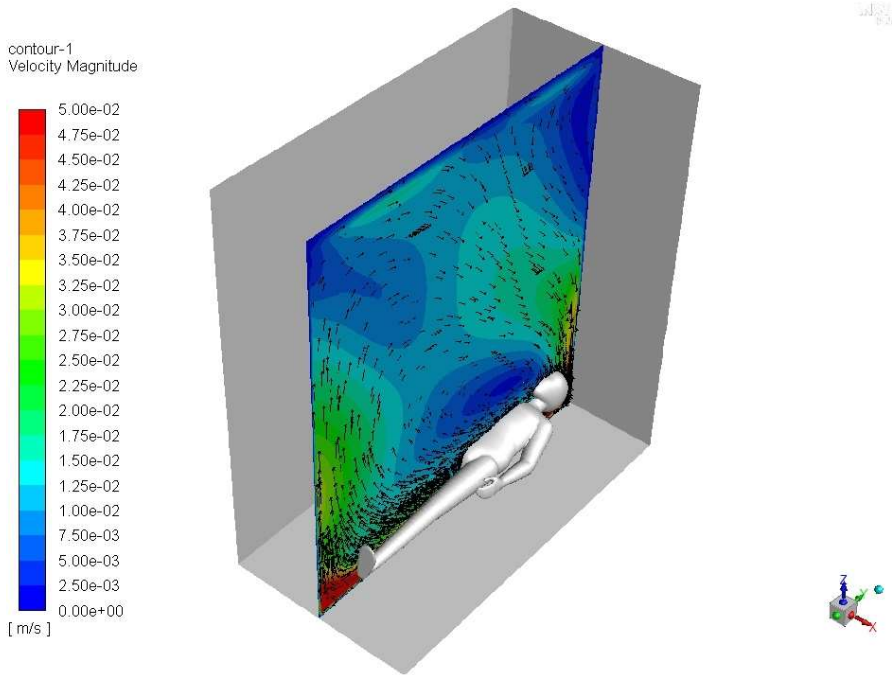
[**Fig. 7**] Three-dimensional temperature fields of the surface of the bed in the mobile home



[**Fig. 8**] Three-dimensional temperature fields on the surface of the bed at a height of 500 mm from the base of the mobile home



[**Fig. 9**] Fields of three-dimensional air temperature on the central cross-section inside the mobile home



[**Fig. 10**] Fields of three-dimensional airflow velocity on the central cross-section inside the mobile home

3.2 Equilibrium for the rate of natural convection heat transfer in the mobile home

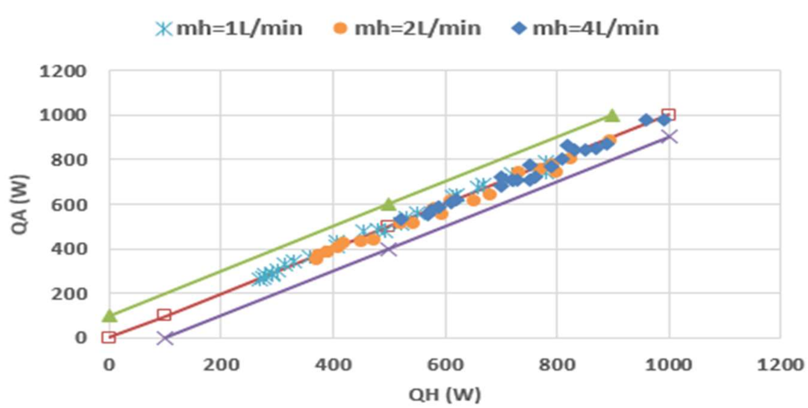
Fig. 11 shows the heating energy supplied by the integrated water bath boiler in the mobile home and the heating energy absorbed by the air. The heating energy per unit time supplied to hot water from the integrated water bath boiler was calculated using Equation (1)

$$Qh = MhCp(Th2 - Th1) \qquad (1)$$

where, Qh represents the heating energy per unit time supplied to hot water from the integrated water bath boiler, Mh represents the mass flow rate of hot water (kg/s), Th1 represents the temperature of hot water at the inlet(K), and Th2 represents the temperature of hot water at the outlet. The heating energy per unit time obtained by the air inside the mobile home was obtained using Equation (2).

$$Qm = MmCpm(Tm2 - Tm1) \qquad (2)$$

where, Qm represents the heating energy per unit time (W)\ absorbed by the air inside the mobile home, Mm represents the mass flow rate of air (kg/s), Tm1 represents the initial temperature (K) inside the mobile home, and Tm2 represents the final temperature of the air inside the mobile home. As shown in Fig. 11, the heating energy supplied by the hot water in the mobile home and the heating energy absorbed by the air inside the mobile home matched well at $\pm 5\%$. Therefore, the experimental results in this study are considered to have secured reliability and accuracy.



[**Fig. 11**] Equilibrium of the heating energy supplied by the integrated water bath boiler and the heating energy obtained by the air in the space inside the mobile home

3.3 Natural convective heat transfer coefficient of air inside the mobile home

Fig. 12 shows the comparative values of the theoretical natural convective heat transfer coefficient and experimental natural convective heat transfer coefficient of air inside a mobile home. Equation (3) represents the heating experimental natural convection heat transfer coefficient of air inside a mobile home

$$Hex = \frac{Qm}{As(Tw - Ta)} \qquad (3)$$

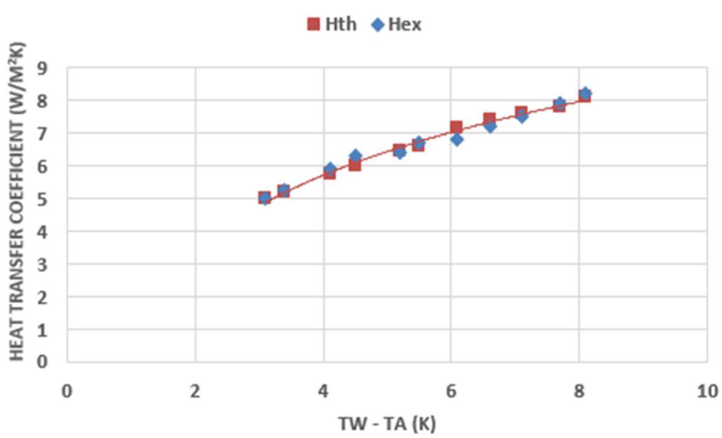
where, Qm represents the heating heat transfer rate (W) of the air inside the mobile home. As represents the heat transfer surface area (m^2) of the surface of the mobile home, Ta represents the indoor air temperature (K) during heating, and Tw represents the wall temperature (K) of the mobile home. Equation (4) represents the Nusselt number of the air for heating inside the mobile home.

$$Nu = 0.826 + \frac{0.387Ra^{0.17}}{1+(0.492/Pr)^2} \qquad (4)$$

where, Pr represents the Prandtl number. The theoretical natural convective heat transfer coefficient of the air inside the mobile home was obtained using Equation (5).

$$Hth = \frac{kf}{L} Nu \qquad (5)$$

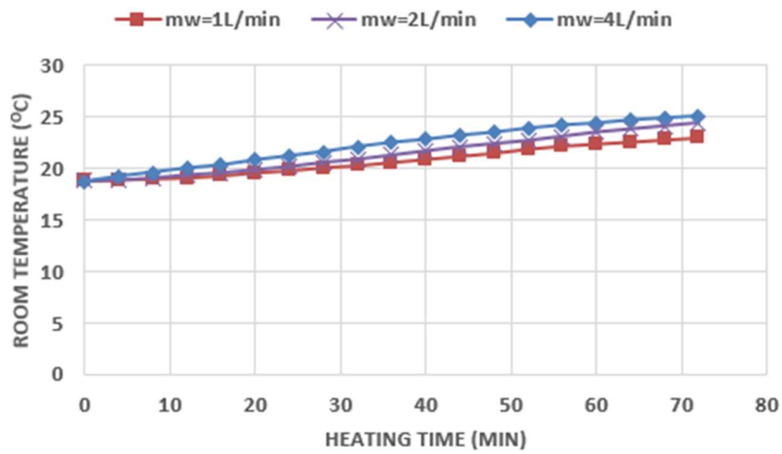
where, kf represents the thermal conductivity coefficient (W/mK) of the air in the heating inside a mobile home. As shown in Fig. 12, the experimental natural convective heat transfer coefficient value in the heating of the mobile home obtained from Equation (3) and the theoretical natural convective heat transfer coefficient value of the air for heating obtained from Equation (5) agreed relatively well throughout the entire range of experiments. Therefore, the reliability and accuracy of the experiment's resultant values on the heating performance of the mobile home in this study are verified.



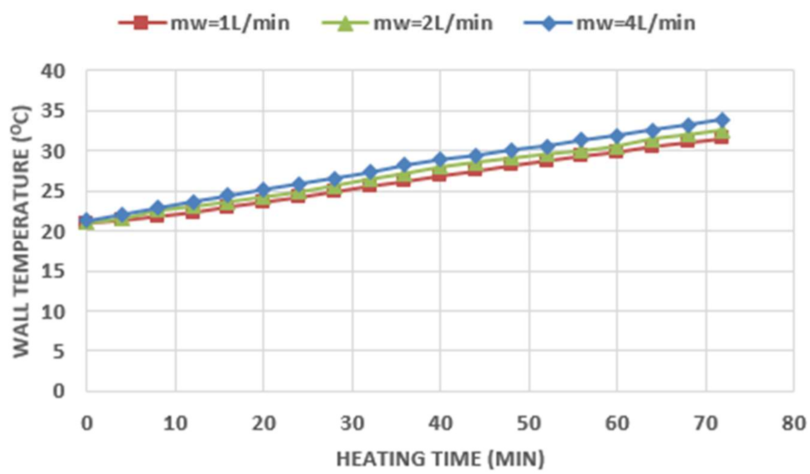
[**Fig. 12**] Comparison of the theoretical natural convective heat transfer coefficient and the experimental natural heat transfer coefficient of the mobile home

3.4 Heating performance of the mobile home

Figures 13 and 14 illustrate the changes in air and wall temperature fields inside the mobile home in response to varying hot water flow rates through natural convection panels embedded in the walls and floor. Experiments were conducted under three flow rate conditions: 1 L/min, 2 L/min, and 4 L/min. As shown in Fig. 13, the air temperature inside the mobile home increased proportionally with the increase in hot water flow rate and consistently rose with heating time. This indicates that the temperature of the hot water supplied by the wall-mounted electric boiler effectively increases, enhancing the heating transfer performance. The results demonstrate that as the hot water flow rate increases, the heating efficiency of the mobile home improves, achieving a balanced heating energy equilibrium, thus verifying the reliability and accuracy of the experimental outcomes. Similarly, Fig. 14 shows that wall temperature increased proportionally with the operating time of the integrated water bath boiler and the hot water flow rate, further confirming that higher flow rates enhance the heat transfer performance of the system, resulting in improved air temperature inside the mobile home. In conclusion, both air and wall temperature data indicate that increasing the hot water flow rate significantly improves the heating performance of the mobile home, with practical implications for optimizing the design and efficiency of heating systems in mobile homes.



[**Fig. 13**] Changes in the air temperature fields inside the mobile home in relation to changes in the velocity fields of hot water circulating on the wall of the mobile home



[**Fig. 14**] Temperature fields in relation to changes in the velocity fields of the hot water circulating on the wall of a mobile home

4. DISCUSSION

The findings provide valuable insights into optimizing heating systems for mobile homes, contributing to improved energy efficiency and occupant comfort. The results indicate a clear relationship between increased hot water flow rates and enhanced heating performance. Specifically, as the hot water flow rate increased from 1 L/min to 4 L/min, both air and wall temperatures showed a proportional rise. This suggests that higher flow rates improve the heat transfer efficiency of the natural convection panels embedded in the walls and floor of the mobile home. First, increasing the hot water flow rate can lead to more uniform temperature distribution, reducing cold spots and enhancing overall comfort for occupants. This improvement is particularly relevant for mobile homes, where space constraints and insulation challenges often result in uneven heating. By optimizing flow rates, manufacturers and homeowners can achieve better thermal regulation and energy efficiency. Additionally, the study's findings suggest potential applications in the design and retrofitting of mobile home heating systems. For example, integrating adjustable flow rate controls in heating systems could allow users to tailor the heating performance to their specific needs and environmental conditions. Such flexibility can contribute to energy savings and increased comfort, making mobile homes more sustainable and livable. Moreover, the observed correlation between flow rate and heating performance underscores the need for comprehensive guidelines and standards in mobile home heating system design. Regulatory bodies and industry stakeholders should consider incorporating flow rate optimization criteria into existing standards to ensure the widespread adoption of efficient heating practices. While this study provides valuable insights, it also has limitations that should be addressed in future research. The experiments were conducted under controlled conditions, which may not fully capture the variability of real-world environments. Future studies should consider testing the heating performance in different climates and occupancy scenarios to validate the findings further. Additionally, exploring the long-term impacts of varying flow rates on system durability and maintenance costs would provide a more holistic understanding of the practical implications. In conclusion, this study demonstrates that increasing the hot water flow rate significantly improves the heating performance of mobile homes. By optimizing flow rates, it is possible to achieve more uniform temperature distribution and enhanced energy efficiency. These findings have important implications for the design, retrofitting, and regulation of mobile home heating systems, contributing to the development of more sustainable and comfortable living environments. Future research should build on these results to explore the broader applications and long-term impacts of flow rate optimization in mobile home heating systems.

5. CONCLUSIONS

This study conducted both analytical and experimental investigations into the three-dimensional temperature and velocity fields, as well as the heating performance, of a natural convection heating system for mobile homes. The findings reveal several key insights into the effectiveness and benefits of such a system. Firstly, the natural convection system was shown to provide uniform temperature fields throughout the mobile home, creating a well-being environment that is beneficial to health. This uniformity in temperature distribution is crucial for maintaining a comfortable indoor climate, which is particularly important in mobile homes that often struggle with uneven heating. Secondly, the agreement between the experimental and analytical results for the three-dimensional air temperature fields confirms the accuracy and reliability of the system's performance. This consistency validates the methodologies used in the study and reinforces the credibility of the findings. Thirdly, the airflow velocity fields generated by the natural convection system were significantly lower than those produced by traditional forced convection heating methods. This lower velocity is beneficial as it reduces drafts and promotes a more stable and comfortable indoor environment, further contributing to the health benefits of the system. Additionally, the study found that the heating energy supplied by hot water and the energy absorbed by the air inside the mobile home were well-matched. This balance indicates efficient energy transfer and effective heating performance. Moreover, the study demonstrated that increasing the mass flow rate of hot water resulted in higher air temperatures within the mobile home, thereby enhancing the overall heating performance. This finding suggests that the system's efficiency can be easily adjusted and optimized based on specific heating needs. The broader implications of these findings suggest that natural convection heating systems can significantly enhance energy efficiency and occupant comfort in mobile homes. The system not only addresses common shortcomings of existing heating solutions but also promotes a healthier indoor environment through its uniform heating capabilities and reduced air velocity. Future research should focus on optimizing the design of convection panels to suit various mobile home configurations and climates. Additionally, exploring the integration of renewable energy sources, such as solar thermal systems, could further improve the sustainability and efficiency of natural convection heating systems. Addressing these areas will provide deeper insights and potentially lead to more advanced and versatile heating solutions for mobile homes. In summary, this study highlights the potential of natural convection heating systems to improve indoor comfort and energy efficiency, offering a promising alternative to traditional heating methods for mobile homes.

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