IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 38, No. 1, March, 2020, pp. 269-273
Journal homepage: http://iieta.org/journals/ijht

Analysis for Thermal Performance and Energy-Efficient Technology of Prefabricated Building Walls

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https://doi.org/10.18280/ijht.380129

Received: 18 August 2019
Accepted: 20 December 2019

Keywords:
prefabricated building, energy-efficient design, composite wall, thermal performance, thermal conductivity

ABSTRACT

At present, prefabricated buildings have been widely used in residential buildings and industrial plants. The energy-efficient design of their walls has increasingly become the focus of design in the construction industry. Taking the commonly used composite walls of prefabricated buildings in Inner Mongolia as the research object, the authors aim to explore the thermal performance of prefabricated building wall under cold conditions, and study the energy-efficient technology by determining the optimal thickness of the insulation layer. The study found that the external envelope structure such as the walls is the main heat dissipation method of the prefabricated building; as the thickness of the insulation layer increases, the thermal conductivity of the wall decreases, and the thermal inertia index increases, showing better insulation characteristics; the heat flux density of the composite wall designed with the external insulation layer was the smallest; the average daily heating power consumption of the composite wall with the polystyrene plastic interlayer was the minimum, and it reduced by 21.65% compared with the no-intermediary insulation layer. The research findings provide guidance and suggestions for the composite wall design and material selection of prefabricated buildings in Inner Mongolia.

1. INTRODUCTION

Building energy efficiency is a rigid indicator of the construction industry. Due to their great advantages in energy efficiency, environmental protection and earthquake resistance, prefabricated buildings have gradually become an inevitable trend in the development of urbanized residential construction projects [1]. Various new types of prefabricated building materials have emerged one after another. In prefabricated buildings, the thermal energy consumption of the wall occupies 20% -50% of the total, and becomes the external maintenance structure with the most heat loss [2]. At present, there are many wall materials for prefabricated buildings, including prefabricated insulation board walls and multi-cavity composite walls etc., which vary in the heat and moisture transfer, engineering cost and energy-saving performance. Taking multi-cavity composite walls for examples, there is a big difference in the heat and moisture transfer of walls between different cavity forms [3]. The heat transfer and energy efficiency characteristics of the wall's envelope structure are closely related to the material. Currently, as a lightweight, high-strength and thermally insulating structural member, the composite wall structure is the most commonly used [4].

In terms of building structure, prefabricated building walls belong to the envelope structure. The thermal system inherent in this envelope structure exhibits dynamic heat transfer characteristics under the action of external thermal signals that change with time [5]. Compared with the energy-saving technology of wall building in foreign developed countries, the unit energy consumption of the prefabricated building wall in China is still much higher than that in developed countries. With the continuous deepening of research and application, the insulation performance indicators related to the wall structure of China's buildings have been also constantly improving [6]. The design of building structure has gradually focused on selecting the walls with different thickness and materials for different regions. Unlike masonry structures and traditional masonry filled walls, the insulation layer of prefabricated building walls can effectively block heat conduction, playing a good role in heat preservation and energy saving [7]. Taking the commonly used composite wall of prefabricated buildings in Inner Mongolia as the research object, this paper attempts to study the thermal performance and the energy-efficient technology of the composite wall under cold conditions by determining the optimal thickness of the insulation layer. This study provides strong support for promoting the composite wall of the prefabricated building.

2. STATUS ANALYSIS FOR PREFABRICATED BUILDING SYSTEMS AND THERMAL CONDUCTION OF WALLS IN INNER MONGOLIA

With the development of prefabricated buildings, the industrialized wall structure has formed, including fully prefabricated shear wall systems, prefabricated sandwich insulation wall systems and double-sided laminated shear wall systems [8, 9]. The most widely used in Inner Mongolia is the prefabricated sandwich insulation wall system, which not only ensures the most basic maintenance and load-bearing functions, but also meets the requirements of fire protection and thermal insulation [10]. The middle insulation layer of the prefabricated sandwich insulation wall system has the same service life as the building, and requires no maintenance during the entire life cycle. Furthermore, the fabricated construction outside the wall can effectively shorten the construction cycle [11]. Figure 1 shows the heat loss ratio of prefabricated buildings in Inner Mongolia. According to the statistics, the heat loss of walls and other external envelope structures account for 41.67%, followed by doors and windows, i.e., 37.96%; the heat loss of the roof, ground and ventilation accounts for about 20%. Thus, the heat loss of the wall and other external envelope structures is the largest.

The wall of the prefabricated building creates an indoor space for humans, as an important carrier for the formation of the indoor thermal environment. Figure 2 shows the heat energy source and loss path of the prefabricated building in Inner Mongolia. The heat energy sources include heating systems, solar radiation, heat dissipation from household appliances and human heat, etc.; the heat loss path includes heat dissipation of the external envelope structure, cold air infiltration, hot water discharge and water vapor removal, etc., of which the most important way of heat loss is heat dissipation of the envelope structure. Some buildings use prefabricated sandwich thermal insulation wall systems as the internal wall, and the add-on sandwich panels as external wall. It has been found by some scholars that the add-on insulation wall panels can achieve lower thermal conduction effect, but as the building's service life increases, the effect decreases [12, 13].

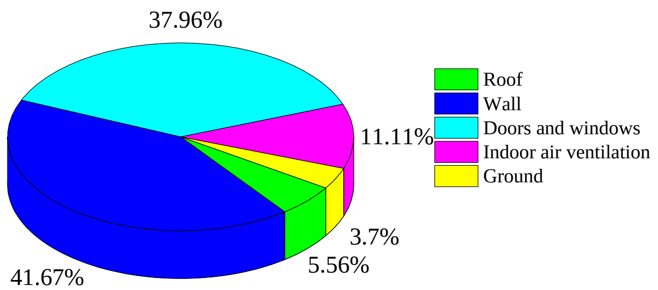

Figure 1. Heat loss ratio of prefabricated buildings in Inner Mongolia

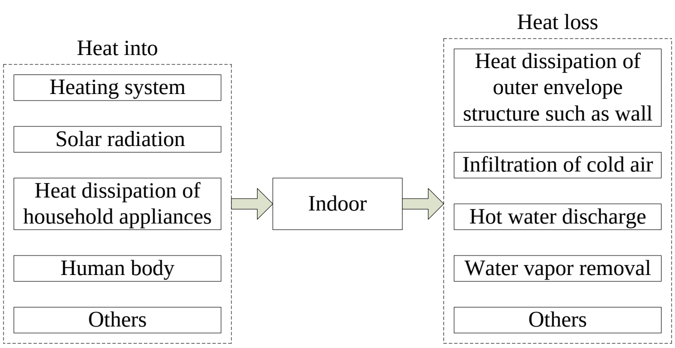

Figure 2. Heat sources and loss path in prefabricated buildings

3. THERMAL PERFORMANCE ANALYSIS OF PREFABRICATED BUILDING WALLS

3.1 Thermal performance of composite wall

The thermal insulation performance and energy-efficient performance of composite walls are superior to ordinary walls. Not only can they be constructed in different shapes to meet people's increasing aesthetic requirements, but also bring the building a modern atmosphere, thus providing favorable conditions for the development of industrialization of construction [14]. Figure 3 is a photo of an assembled composite wall, which is divided into different composite walls according to different insulation materials. Based on the design standards for energy efficiency of wall building, the thermal performance of the wall depends on the heat transfer coefficient, heat transfer resistance and thermal inertia system. The thermal resistance R of the composite envelope structure is calculated as shown in Eq. (1) and (2):

$$R=R_1+R_2+\cdots+R_n \tag{1}$$

$$R_i=\frac{\delta_i}{\gamma_i} \tag{2}$$

where, R_i is the thermal resistance of the i-th layer material, δ_i is the thickness of the i-th layer material, and γ_i is the thermal conductivity of the material.

The thermal inertia index D of the composite envelope structure is calculated as shown in Eq. (3) and (4):

$$D=D_1+D_2+\cdots+D_n \tag{3}$$

$$D_i=R_i*S_i \tag{4}$$

where, D_i is the thermal inertia index of the i-th layer material, and S_i is the heat storage coefficient of the material.

The heat transfer coefficients K of the composite envelope structure is calculated as shown in Eq. (5):

$$K=\frac{1}{R_0} \tag{5}$$

Figure 3. Photo of assembled composite wall

3.2 Thermal performance analysis of composite wall

Figure 4 shows the thermal performance and characteristics of different composite walls. The interlayer of composite walls generally includes a closed insulation layer, a natural flow insulation layer, and a mechanical flow insulating layer. Among them, the closed insulation layer plays the role of thermal insulation and improves the indoor thermal comfort; the natural flow insulation layer realizes passive cooling, natural ventilation and hot air heating in the room; the mechanical flow insulation layer achieves indoor hot air heating and fresh air supply, and reduces the transfer of heat load. This study aims to explore the thermal performance of different composite walls. For this, the laboratory tests were conducted on walls with different interlays, to probe into the thermal conductivity and thermal inertia index of different-thickness insulation walls.

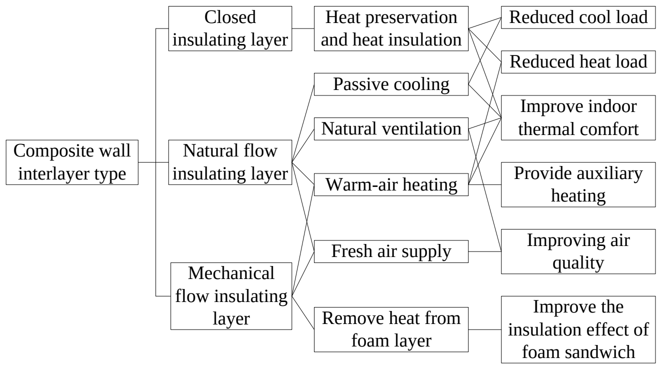

Figure 4. Thermal performance and characteristics of different composite walls

Table 1. Conversion of thermal parameters of middle layer of composite wall

Material characteristics	Density kg/m^3	Heat conductivity coefficient J/(m·s·k)	Specific heat capacity kJ/(kg·K)
No intermediary	335.47	0.6515	0.964
Polystyrene plastics	347.34	0.1426	1.719
Perlite powder	553.42	0.1914	1.083
Loose rice husk	431.06	0.2133	0.759

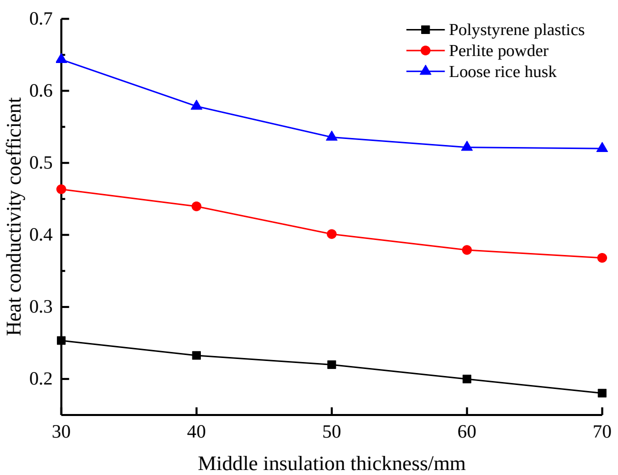

Figure 5. Thermal conductivity of walls with different intermediate insulation thickness

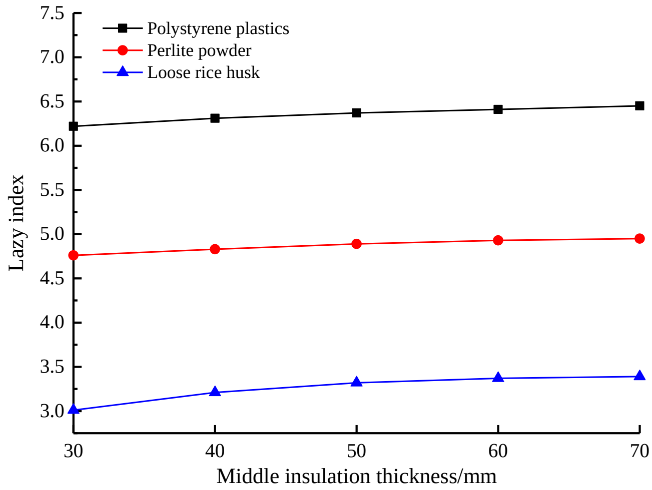

Figure 6. Thermal inertia index of wall with different intermediate insulation thickness

Table 1 lists the thermal parameters converted from the middle layer of the composite wall, including the density, thermal conductivity and specific heat capacity of the no-intermediary materials and three other different materials. Figure 5 shows the thermal conductivity of the wall with different thickness of the middle insulation layer. It can be clearly seen that as the thickness of the insulation layer increases, the thermal conductivity of the wall decreases, showing a better thermal insulation effect. Furthermore, using the loose rice husk as the material of the insulation layer, as the thickness of the insulation layer increases, the thermal conductivity decreases less; as the thickness is greater than 50mm, it has little effect on the insulation effect. Figure 6 shows the thermal inertia index of the wall with different thickness of the middle insulation layer. It can be clearly seen that as the thickness of the insulation layer increases, the inertia index of the wall increases, showing the test results opposite to the thermal conductivity.

4. ENERGY-EFFICIENT ANALYSIS OF PREFABRICATED BUILDING WALLS

4.1 Analysis of building energy consumption of different composite walls

A fixed indoor space ensures a stable environment. The influence of outdoor temperature change and solar radiation intensity on the indoor environment directly determines the quality of the building. In the actual project in Inner Mongolia, the thermal performance of the different prefabricated building walls is not stable. It is of great significance to explore the energy consumption of different composite walls during the energy-saving design of the walls. The energy-efficient effect of the building structure is positively related to the thermal performance. Energy consumption analysis was carried out using Equest energy consumption simulation software, which can set meteorological parameters and heat energy sources and losses, with reference to the existing composite wall design. Figure 7 compares the heat flux density of different walls. It can be seen that the fluctuation of the heat flux density of the closed insulation layer was relatively small, and its heat flux density value was greater than other composite walls at any time; that of the natural flow insulation layer was in the second place; that of the mechanical flow insulation layer in the composite wall was the lowest, but the fluctuation of its heat flux density was the largest, mainly related to the convection heat transfer of the composite wall.

The setting of the insulation layer also has an important impact on the energy saving of the wall. Figure 8 shows the heat flux density of the composite walls with different insulation layer settings. It can be clearly seen that the heat flux density of the composite wall with external insulation layer was the smallest, mainly because the external insulation layer can reduce the heat flux density of the heat bridge; followed by the composite wall with the built-in insulation layer, because the built-in insulation layer occupies the indoor pore size. These two types of insulation layers are mostly used. For the convenience of calculation parameter setting, this paper only calculates the daily heating power consumption of prefabricated sandwich-type composite walls. Figure 9 shows the average daily heating power consumption of different composite walls. Compared with the non-intermediary wall, the daily heating power consumption of the interlays/middle layers made of polystyrene plastic, Perlite powder and loose rice husk decreased by 21.65%, 15.86% and 8.30%, respectively.

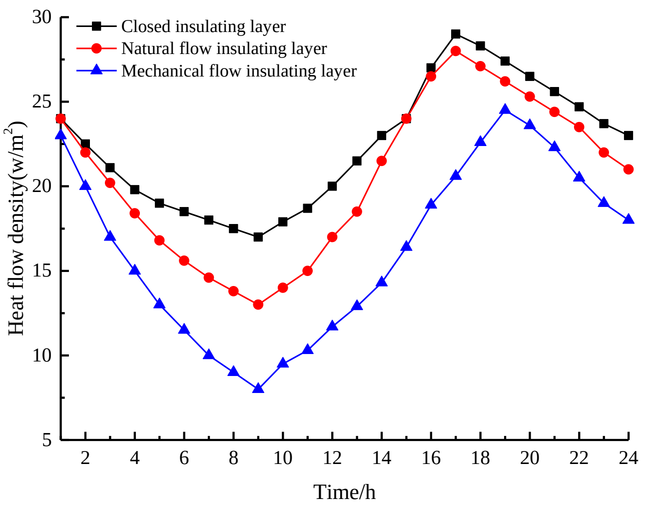

Figure 7. Comparison of heat flux of different walls

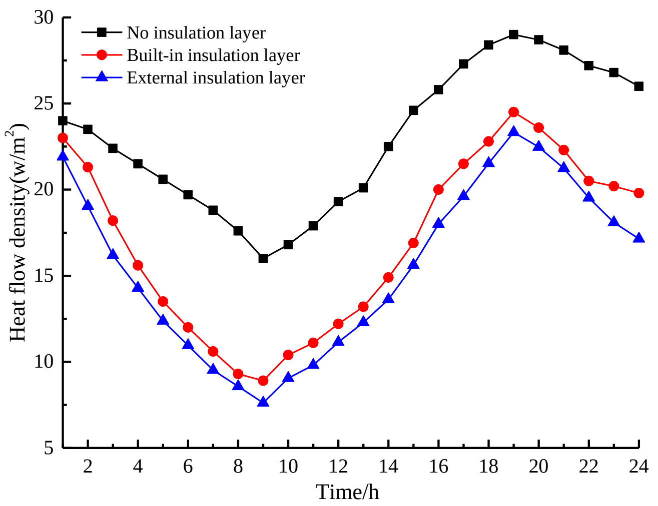

Figure 8. Heat flux of composite wall with different insulation layer settings

Figure 9. Average daily heating consumption of different composite walls

4.2 Economic analysis for composite walls of prefabricated buildings

At present, there are generally two types of insulation layers for composite walls of fabricated buildings: external insulation layers and built-in insulation layers. The external insulation layer basically eliminates the influence of thermal bridges, effectively improves the waterproofness of the walls, and facilitates the future energy-saving renovation of buildings, but requiring high cost, and later maintenance and resetting; the built-in insulation layer effectively protects the insulation materials, ensuring the insulation materials to have the same service life as the buildings. However, such layer is prone to thermal bridges, and is detrimental to the seismic performance of buildings. The comparative analysis for the heat flux density of the two composite walls found that the heat flux density of the two insulation layers is not much different, and the external insulation layer has a relatively lower heat flux value, ensuring a better energy saving effect. For economic considerations, composite walls of sandwich-type insulation layer should be used, which can be prefabricated in batches, and the insulation layers with mechanical flow interlayer have better thermal performance. By comparing the average daily heating power consumption of the three interlayer, the use of polystyrene plastic in the interlayer in Inner Mongolia can achieve greater economic benefits.

5. CONCLUSIONS

Taking the commonly used composite walls of prefabricated buildings in Inner Mongolia as the research object, this paper aims to explore their thermal performance under cold conditions, determines the optimal thickness of the insulation layer, and studies the energy-efficient technology of the composite wall. The specific conclusions are as follows:

(1) The main sources of heat energy for prefabricated buildings in Inner Mongolia include heating systems, solar radiation, heat dissipation from household appliances, and human heat; the heat loss path include heat dissipation of external envelope structures, cold air infiltration, hot water discharge, and water vapor removal etc., and the most important way of loss is heat dissipation of the external envelope structure.

(2) As the thickness of the insulation layer increases, the thermal conductivity of the wall decreases, showing better thermal insulation; as the thickness increases, the thermal inertia index of the wall increases, showing the test results opposite to the thermal conductivity.

(3) The heat flux density of the closed insulation layer fluctuates relatively small, and it is greater than the insulation layers with natural flow interlayer and the mechanical flow interlayer at any time; the composite wall with mechanical flow interlayer has the smallest heat flux density value, but its fluctuation of the heat flux density is the largest, mainly related to the convective heat transfer of the composite wall.

ACKNOWLEDGMENT

This paper was supported by Inner Mongolia Natural Science Foundation Project (No.: 2018MS05049).

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