

Dynamic thermal performance of prefabricated temporary exterior wall using cooling water in the cooling season

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Abstract. The acceleration of urbanization has led to a continuous increase in various types of buildings. In the hot season, cooling systems cool buildings and improve their comfort. However, traditional cooling methods require more energy consumption and greenhouse gas emissions. This paper designs a prefabricated building exterior wall with embedded pipes based on water cooling system reduces the output of traditional cooling way in building cooling. The innovation of this research is using the embedded pipe to improve the thermal properties of exterior walls, bonding the embedded pipe and exterior wall structure together. The results show that the embedded prefabricated building exterior walls are designed to control the indoor wall temperature to around 28 °C in summer. And the temperature on the surface of the inner liner cavity is always above 25.5 °C. The overall trend shows a decrease followed by an increase. At noon, the surface temperature on the cavity side of the inner lining plate is the lowest, about 25.8 °C. The larger the indoor and outdoor temperature difference, the better the cooling effect of the structure on the building. This study's application can help reduce energy consumption and carbon emissions effectively.

Keywords: Thermal performance; Prefabricated buildings; External walls; cooling water; Heat transfer characteristics

1. Introduction

With the rapid development of the global economy and sustained population growth, the level of urbanization continues to rise, leading to a sharp increase in the number of urban buildings [1]. Although the construction industry can drive urban development, it also consumes a large amount of energy, especially the sharply increased demand for cooling in summer [2]. According to a survey by the International Energy Agency 2020, the total carbon emissions from China's construction operations in 2020 were 2.16 billion tons of carbon dioxide, accounting for 21.7% of the country's carbon emissions [3]. The cooling methods of traditional buildings, such as central air conditioning systems, mostly rely on electricity, which consumes more energy and causes more carbon emissions[4]. The peripheral structure is the main structure for building heat loss, and the outer wall is one of the peripheral structures of buildings, which has a high loss of heat transfer in buildings. Thus improving the thermal performance of peripheral wall structures can effectively reduce the cooling consumption and carbon emissions of buildings [5-6]. Water cooling is a commonly used cooling method in other fields, which consumes low energy and has no carbon emissions during operation [7]. Therefore, to reduce the energy consumption of building refrigeration and reduce building carbon emissions, this study proposes to use water cooling technology to transform the exterior wall structure of prefabricated buildings. The innovation of this paper lies in the use of embedded pipe structures to improve the exterior walls of buildings, enabling the water cooling system to be integrated with the exterior wall structure. Through this method, building exterior wall structures is transformed, reducing the output of power-dependent

equipment such as central air conditioning in building cooling systems, and decreasing building carbon emissions during the cooling season.

2. Thermal Performance of Prefabricated Building External Wall Structures

2.1 A Heat Transfer Model For Embedded Tube-assembled Exterior Walls

The outdoor temperature is usually higher than the indoor temperature during the cooling season of summer, and the area near the outdoor side wall will be heated first. The air inside the cavity will be heated. If the cavity exits inside the wall, forming a hot air flow at the upper end of the wall cavity [8]. Based on this characteristic, the exterior wall structure of prefabricated buildings is designed as a wall structure with cavities. Based on this characteristic, the exterior wall structure of prefabricated buildings is designed as a wall structure with cavities. The wall cavity should be located on the indoor side of the wall to reduce indoor temperature. Water cooling systems are usually implemented through pipelines or tanks, with small pipe volumes, high cooling efficiency, and wall cavities. The newly designed pipeline system adopts a water-cooled system as the prefabricated exterior wall structure of the building, as shown in Fig. 1.

The embedded pipe-type exterior wall is shown in Figure 1, which consists of a wall on the outside and a cavity on the indoor side. There is a partition layer in the cavity on the indoor side to distinguish the wall cavities, but the wall cavities are still connected from top to bottom. A water-cooled pipeline system is installed in the upper part of the indoor side cavity. Once the outdoor temperature rises, the air near the main wall in the cavity is heated through the main wall. The heated hot air forms an upward hot air flow, which transitions to the condensation pipeline through the air channel on the upper side of the wall. After the hot air comes into contact with the condensation pipeline, a sinking cold air flow is formed, which returns from the air channel at the bottom of the cavity to the outer cavity, achieving building cooling. The material of the condenser tube directly affects the heat exchange efficiency. Common condenser tube materials include copper tubes, iron tubes, carbon steel pipes, etc. Among them, the copper tube has the strongest corrosion resistance and the highest thermal conductivity efficiency. Therefore, copper condenser tubes are chosen for research. The types of condenser pipes include straight pipes, spiral pipes, and ribbed pipes. Ribbed pipes have the effect of enhancing convective heat exchange. It is better to choose ribbed pipes as the condenser pipe type. In this study, circular ribbed pipes are used in the design of wall structures. Before analyzing the dynamic thermal performance of the wall structure, it is necessary to establish its geometric model. Assuming that the wall material and other heat-conducting media are uniform media, the water-cooled pipes are parallel structures, and the temperature difference between the inlet and outlet is consistent. The air inside the wall cavity and the cooling water in the condenser are both fluids. When analyzing its heat transfer characteristics, it is necessary to establish its continuity equation, momentum equation, and energy equation. If the fluid flow is turbulent, a corresponding model needs to be established. Fluid flow conforms to the conservation of mass, and the continuity equation of fluid in steady-state flow is shown in equation (1) [9].

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \quad (1)$$

Where x , y and z represent the three axes on the coordinate axis, v_x , v_y and v_z stand the velocity components of a fluid in three directions. Fluid momentum is a description of the fluid velocity field, following the conservation of momentum. The vector form of the momentum equation is shown in equation (2) [10].

$$\rho \frac{d\vec{V}}{dt} = \rho \vec{g} - \nabla \vec{p} + \mu \nabla^2 \vec{V} \quad (2)$$

Where ρ represents fluid density, \vec{V} represents fluid velocity, \vec{p} stands represents fluid pressure, μ is the dynamic viscosity of fluids and g is Gravitational acceleration. The energy equation is a description of the temperature of a fluid, following the first law of thermodynamics. If the fluid is ideal, the energy equation is shown in equation (3) [11].

$$\frac{\partial(\rho T)}{\partial t} + \text{div}(\rho v T) = \text{div}\left(\frac{k}{c_p} \text{grad} T\right) \quad (3)$$

Where T is fluid temperature, c_p stands the specific heat capacity of the fluid and k represents the heat transfer coefficient of the fluid. The building cooling system adopts the form of thermal radiation for building cooling, therefore, a radiation model of the wall structure needs to be established to study the surface to surface model for calculating the long-wave radiation model of the wall surface. Assuming that the absorption rate and reflectivity are equal in the entire wall structure, the energy leaving the given surface can be expressed as equation (4).

$$q_{out,a} = \varepsilon_a \sigma T_a^4 + \rho_a q_{in,a} \quad (4)$$

Where $q_{out,a}$ and $q_{in,a}$ are the departure energy and entering energy, respectively. ε_a stands emissivity and σ represents the Stefan Boltzmann constant. The energy expression of the incident surface is shown in equation (5) [13].

$$q_{in,a} = \sum_{j=1}^N q_{out,j} F_{aj} \quad (5)$$

In equation (5), F_{aj} represents the angle coefficient between any two surfaces; N indicates the quantity of all surfaces.

2.2 Model Solving

The heat exchange and air circulation in the exterior wall cooling model of a prefabricated building with embedded pipes are completed. Air can be regarded as a continuous fluid, and the solution problem of this model can be regarded as the solution of the fluid motion state. Numerical calculations can effectively solve this type of problem [14]. When using this method for model solving, it is necessary to perform grid partitioning on the exterior wall cooling model of the building being studied and constructed. When dividing the grid, the influence of grid size on the calculation results cannot be ignored, and it is necessary to verify the independence of the grid. The steps for checking the independence of the grid are as follows: firstly, use the heat on the outer wall surface of the room and the heat on the inner side wall surface as a reference; Secondly, change the size of the grid; Finally, based on the number of grids, calculate the reference quantity and analyze the impact of grid size on the reference quantity. The grid division of the wall structure is studied as shown in Fig. 2.

The heat transfer characteristics of wall structures are influenced by some structural parameters. The water cooling system is the core of the constructed exterior wall cooling model, and the number of condenser pipes is an important parameter of this system. The influence of the number of cooling pipes on the heat transfer coefficient of the wall can be divided into two aspects: the heat exchange area between the hot air and the condenser pipes, and the rate at which the hot air passes through the condenser pipes. In general, the more cooling pipes there are, the larger the heat exchange area between the hot air and the condenser pipes, and the better the cooling effect. However as the number of condensing tubes increases, the rate at which hot air settles towards the lower part of the cavity after condensation will decrease, thereby affecting the overall condensation effect of the structure. The cooling efficiency of a water cooling system is not only related to the number of condenser tubes but also to the temperature of the cooling water. Cooling water is the main heat source for the designed building cooling system. As the water temperature of the cooling water increases, the temperature difference between the condenser pipe and the hot air will decrease, decreasing the heat exchange rate between the hot air and the condenser pipe. Therefore, when selecting condensate, the lower the liquid temperature, the better the cooling effect of the cooling

system. In the external wall cooling model, the partition layer directly affects the flow of air and is also an important structure that affects heat transfer characteristics. The partition layer plays a role in separating hot and cold air in the research and design of cooling systems, promoting automatic circulation of hot and cold air. The impact of the partition layer on the cooling system is mainly related to the thermal resistance of the partition layer. The larger the thermal resistance, the better the separation effect of the partition layer on cold and hot air. The influencing factors of heat transfer characteristics are shown in Fig. 3.

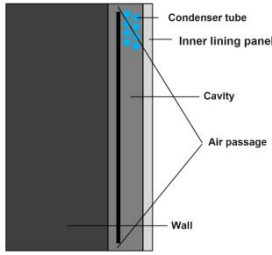


Fig. 1 Prefabricated building exterior wall structure based on water-water-cooling system

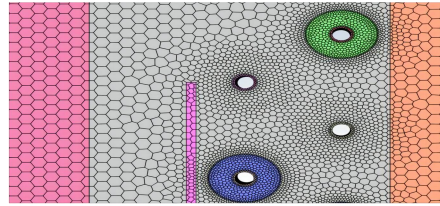


Fig. 2 Grid division of wall structure

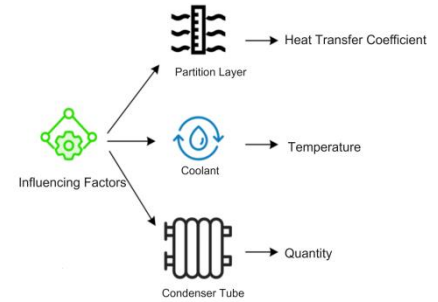


Fig.3 Influencing factors of heat transfer characteristics

After determining the influence factors on the heat transfer characteristics in the cooling system, the heat transfer model of the embedded pipe assembly building exterior wall based on cooling water can be solved. After grid processing, the control equations of the model have been discretized and are solved by coupling fluid pressure and velocity. It can also be solved through the solver of Fluent software. There are two types of solvers in Fluent software, one starts from pressure, and the other starts from density. The solver that starts with pressure adopts a pressure correction algorithm, which is suitable for incompressible fluid motion [15]. The model constructed for research is a typical incompressible fluid model, and a solver that starts with pressure can be selected.

3. Dynamic Thermal Performance Analysis of Prefabricated Building Exterior Walls

3.1 Structural Dimensions And Parameter Settings

The designed cooling system is used for civil buildings. The wall width studied and designed is 1m, the height is 3.3m, the wall cavity width is 0.06m, the hot air circulation channel of the wall cavity is 0.02m wide, and the cold air circulation channel is 0.04m wide. The diameter of the condenser pipes in the cooling system is 15mm, with 8 condenser pipes. The spacing between the fins of the condenser pipes is 6mm, and the thickness of the fins is 0.3mm. The specific structure is shown in Fig. 4.

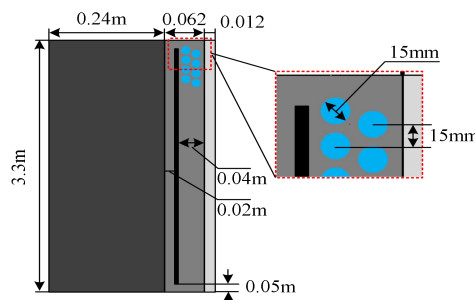


Fig. 4 Model structural parameters

The designed cooling system mainly considers summer usage. When conducting structural dynamic thermal performance analysis, the boundary conditions are set as shown in Table 1.

Table 1. Boundary condition settings

Boundary	Condition	Convective heat transfer temperature (W/m ² *K)	Convective heat transfer coefficient (°C)
Inner surface of inner lining panel	Convection	25	7
External wall surface	Convection	50	24
Cavity	Symmetry plane	/	/
Inner wall of condenser tube	Constant wall temperature	25	/

3.2 Dynamic Thermal Performance Analysis Of Wall Structures

When analyzing the dynamic heat transfer performance of the wall structure, the constructed wall structure is placed towards the south of the building for dynamic thermal performance analysis. The temperature changes on the inner and outer surfaces of the wall are shown in Fig. 5.

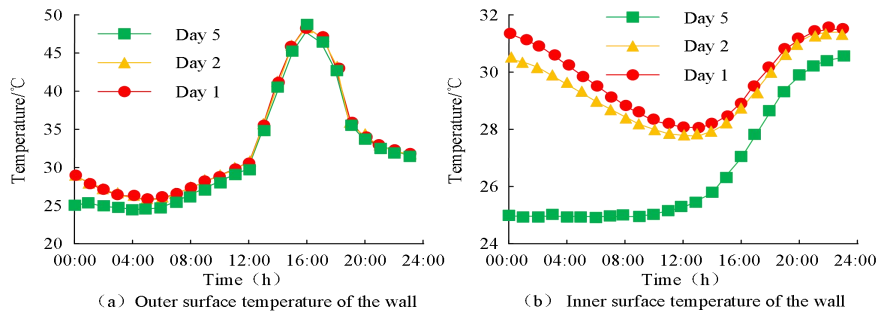


Fig. 5 Dynamic changes in wall temperature

Fig. 5 (a) shows the temperature changes on the outer surface of the wall. On the first and second days, the temperature on the outer surface of the wall was consistent and below 30 °C before noon,. At 5 am, the temperature on the outer surface of the wall was the lowest, only around 24 °C. During the period from 12:00 noon to 4:00 pm, the surface temperature of the wall on the first, second, and fifth days all rapidly rises, reaching a maximum of around 48 °C. Then it began to decline. After noon, the sun shines directly on the outer surface of the wall, causing a rapid increase in surface temperature. After 4 pm, the sun gradually shifts westward, and the amount of solar radiation decreases, causing the temperature of the outer surface of the wall to begin to decrease. Fig. 5 (b) shows the temperature changes on the surface inside the wall. It can be seen that on the first and second days, before noon, the surface temperature inside the wall showed a gradually decreasing trend, reaching its lowest point at noon, and then slowly rising. When the temperature difference between the inside and outside of the wall is small, the cooling system is in standby mode, and the surface temperatures inside and outside are the same. After the temperature on the outer surface of the wall starts to rise, the cooling system starts to operate, promoting a decrease in the surface temperature inside the wall and achieving building cooling. On the fifth day, due to the initial low temperature on the inner surface of the wall, the temperature on the inner surface of the wall showed a continuous upward trend.

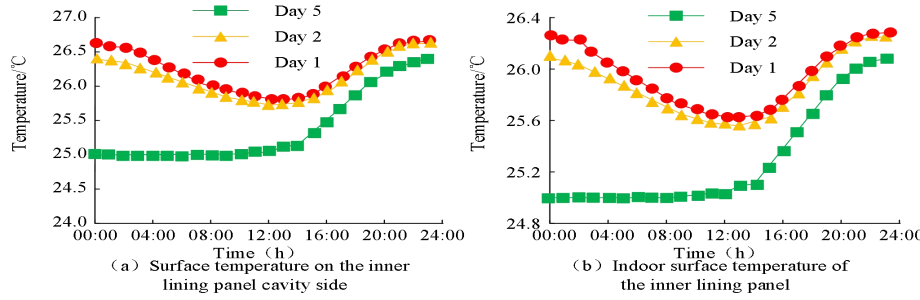


Fig. 6 Dynamic Temperature Changes of Inner Lining Panel

The temperature change of the inner lining plate is shown in Fig. 6. Fig. 6 (a) shows the surface temperature change on the cavity side of the inner lining plate. It can be seen that on the first day, the surface temperature on the cavity side of the inner lining plate remained above 25.5 °C. The overall trend shows a decrease followed by an increase. At noon, the surface temperature on the cavity side of the inner lining plate is the lowest, about 25.8 °C. The dynamic trend of temperature change on the second day is consistent with that on the first day, but the surface temperature of the inner lining panel cavity before noon is slightly lower than that on the first day. On the fifth day, due to the initial low temperature, the dynamic trend of the overall temperature showed that it remained unchanged before noon and gradually increased afternoon. Fig. 6 (b) shows the changes in surface temperature inside the inner lining panel. It can be seen that the changes in surface temperature inside the inner lining panel are consistent with the changes in surface temperature on the cavity side of the inner lining panel, both showing a trend of first decreasing and then increasing. However, the lowest surface temperature inside the inner lining panel was taken at 1 pm, about 25.6 °C. After 3 pm, it gradually rises. The temperature change of the interior surface of the inner lining panel on the fifth day is consistent with the temperature change of the inner lining panel cavity side surface. On the first and second days, the outdoor weather changes significantly. Therefore, the closer the time is to noon, the higher the wall temperature, the greater the indoor and outdoor temperature difference, and the better the cooling effect of the condensation system. After the indoor and outdoor temperature difference decreases, the heat exchange efficiency of the condensing system also decreases, and the absorption temperature of the condensing tube also decreases. Therefore, the dynamic temperature changes of the wall are all around noon as the turning point.

4. Conclusion

To reduce the energy consumption of building cooling and the carbon emissions caused by building cooling, a prefabricated exterior wall structure of a green cooling system was studied and designed. The study aims to achieve building cooling by adding a wall cavity to the exterior wall structure and installing a water cooling system inside the cavity. This cooling system relies on heat transfer under the temperature difference between inside and outside to achieve building cooling. The results showed that during the period from 12 noon to 4 pm, the temperature on the outer surface of the wall rapidly increased, reaching a maximum of around 48 °C. After 4 pm, the temperature on the outer surface of the wall began to significantly decrease. Before noon, the surface temperature inside the wall gradually decreases under the action of the cooling system. The temperature on the surface of the inner liner cavity is always above 25.5 °C. The overall trend shows a decrease followed by an increase. At noon, the surface temperature on the cavity side of the inner lining plate is the lowest, about 25.8 °C. Research on embedded prefabricated building exterior walls based on water cooling system design can reduce the energy consumption and carbon emissions of traditional electricity-based cooling methods. Although the research and design of the embedded pipe assembly type exterior wall structure can meet the cooling needs of summer buildings, it cannot completely replace traditional cooling methods. In the future, the cooling effect

of this structure will be further improved, completely replacing traditional cooling methods, and further reducing the energy consumption and carbon emissions of building cooling.

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