Numerical Simulation of Thermal Performance in Hollow-structure Aluminum of Bullet Train

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Abstract. In order to know the characteristic of heat transfer performance in hollow-structure aluminium, the flow and heat transfer in it of bullet train “Fuxing” was numerical simulated. Changes for the equivalent thermal conductivity under the influence of four factors—the temperature difference, wall thickness, rib thickness and number of cavities, were studied and analysed separately adopting control variate numerical method. Numerical simulation results showed that the influence of temperature difference and wall thickness on the equivalent thermal conductivity of profiles were limited; the number of cavities and rib thickness were the main factors affecting the equivalent thermal conductivity of profiles, with the number of cavities and rib thickness increasing, the equivalent thermal conductivity of hollow aluminium increased, and viced versa. In the practical application, proper parameters of hollow-structure were selected to reduce heat transfer and energy consumption of train.

1. Research Background and Significance
It is important for lightweight car body to develop modern high-speed train. With the stainless steel material being replaced as extruded hollow-structure aluminum, it lowers the fees of train’s operation and maintenance while reducing the weight of train [1]. And owning the good plasticity, easy extrusion, excellent sound insulation, heat preservation as well as recyclability, it gradually becomes the most important part of train’s body. And aluminum alloy is the main material for train construction. Therefore, it is important to obtain equivalent thermal conductivity in complex coupled heat transfer process for hollow aluminum that composite structure. Nowadays, there have been large results of study on the extruded hollow-structure aluminum and technique engineering, but there is little study for heat transfer of it. Hui Yuan [2] and Jinlei Jiang [2] did experiment to measure thermal conductivity, Huasheng Xiong [3] measured thermal conductivity of aluminum extrusion by using steady flat plate method, Xiaojing Ma [4] studied the relationship between thermal conductivity and position of the hot wall related to the direction of gravity. Based on above study, the relationship between equivalent heat transfer coefficient on hollow-structure aluminum and temperature difference, rib thickness and cavity amount discussed in this essay.

2. Hollow-structure Aluminum Heat Transfer Model Establishment

2.1. Geometric Model
In accordance with the requirement, the hollow-structure aluminum is studied by using control variate method in this essay, and makes the simulation research for four influence factors, such as temperature
difference (T), wall thickness (H), rib thickness (L) and number of cavities (N). The structure of hollow-structure aluminum is shown as figure 1.

![Figure 1. Hollow aluminum structure schematic](image)

In this experiment, the cavity of hollow-structure aluminum is triangular and the solid walls of it are all made from aluminum alloy material. The control variables are shown in Table 1. The natural convection of air in the cavity is aroused by the buoyancy force which is made by density difference, the air density adopts the model of Boussinesq, as well as the average temperature of high and low wall temperature sets as heat expansion coefficient. The heat transfer of hollow-structure aluminum has been made through following three ways: (1) heat conduction of hollow-structure aluminum; (2) radiation heat transfer between cavity surfaces; (3) convective heat transfer of internal gases. In the process of heating, aluminum alloy is passed large amount of heat to make the average temperature of hollow wall equal, and radiation heat transfer in the wall of hollow metal is very weak [3, 4], so it ignores the radiant heat transfer of air inside the cavity.

| Table 1. Variable list |
|------------------------|
| temperature difference (K) | 1, 2, 5, 10, 20 |
| wall thickness (mm) | 1, 2, 4, 6, 8 |
| rib thickness (mm) | 1, 2, 4, 6, 8 |
| cavity number | 7, 9, 11, 13, 15 |

2.2. Physical Model

Only the one-dimensional heat transfer of thickness direction for hollow-structure aluminum is considered of this model, the heat transfer of sided direction is ignored, and one-dimensional steady-state heat equation along the direction of hollow-structure aluminum.

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right)
\]  \hspace{1cm} (1)

Where, \(\rho\) is the effective density, \(C\) is the effective specific heat capacity, to be obtained by weighted average in accordance with the area ratio between air and aluminum alloy separately. The thermal property parameters of aluminum alloy and air in the cavity at the operating temperature are shown in Table 2.

| Table 2. Thermophysical parameters of material |
|-----------------------------------------------|
| material | density \(\rho\) [kg/m\(^3\)] | specific heat \(C_p\) [J/(kg·K)] | thermal conductivity \(\lambda\) [W/(m·K)] | Viscosity \(\mu\) [10-5kg/(m·s)] | Coefficient of Thermal Expansion [10-5K-1] |
|----------|-----------------|-----------------|-----------------|----------------|-----------------|
| aluminum alloy | 2730 | 873 | 202 | - | 2.117 |
| air (281.65K) | 1.2539 | 1005 | 0.02496 | 1.752 | 355 |
2.3. Calculation Condition Setting

In addition to the above computing, the initial condition and the boundary condition needs to be set. The first boundary condition is adopted for the hollow aluminum alloy heat transfer simulation in this essay. Taking the example of winter experiment with 2K of temperature difference, the external temperature outside the whole train is 280.65K as low temperature of outside wall, the upper and lower wall of hollow-structure aluminum is \( T_1=282.65K, \ T_2=280.65K, \) temperature load \( \Delta T=2K \). Only considering the heat transfer about internal and external temperature difference, its two-sided wall can be set as insulation condition, and cavity and interface of hollow-structure aluminum can be seen as coupled heat transfer.

The control volume method and the uncoupled steady-state implicit format are used to solve the governing equations, and the laminar flow model is used to calculate the simulated heat transfer and flow. The coupled pressure and speed adopt Simples algorithm. The convection term adopts a second-order upwind scheme. Except for the absolute value of energy calculation residue, the definition of convergence condition is less than \( 1 \times 10^{-8} \), the others are not less than \( 1 \times 10^{-4} \).

2.4. Calculation of Equivalent Thermal Conductivity

The heat performance of hollow aluminum is mainly characterized by equivalent thermal conductivity. The equivalent heat transfer coefficient of hollow aluminum can be shown as:

\[
\lambda_{eq} = q \delta / (T_1 - T_2)
\]

Where, \( \lambda \) is equivalent thermal conductivity, \( q \) is the total surface heat flow density under steady state, \( \delta \) is the thickness of hollow aluminum, \( T_1 \) is the thickness of hot side, \( T_2 \) is the temperature of cold side. Through the final calculation result of above model, and combined above equation, the equivalent thermal conductivity of hollow-structure aluminum can be found.

3. Analysis of Calculation Results

3.1. Hollow-structure Aluminum Heat Transfer Characteristics
The above figure shows temperature cloud distribution of the hollow-structure aluminum when temperature loading of hollow-structure aluminum is \( \Delta T = 2 \text{K} \), the high-temperature wall has same distribution trends corresponding to temperature in the cavity, so does the low temperature. It can be predicted that the natural convection is not so strong from the temperature fluctuation range and the natural convection has the limited impacts on equivalent heat transfer coefficient.

3.2. The Influence of Structure Parameters on the Heat Transfer Performance

In order to properly design the insulation of hollow-structure aluminum, the impact of each structural parameter on heat transfer is studied by adopting control variate. Figure 3 to figure 4 is context diagram of structure parameters of hollow aluminum and equivalent thermal conductivity.

![Figure 3. The influence of temperature difference (a) and wall thickness (b) of hollow aluminum on equivalent thermal conductivity](image)

From figure 3 (a), it is known that although there are some fluctuations for the equivalent thermal conductivity coefficient of hollow-structure aluminum under the different temperature, the numeric change is very little. The simulation result shows that there is little impact for temperature change of the equivalent thermal conductivity coefficient on hollow-structure aluminum, which shows it is very weak for natural convection in the cavity.

From the figure 3 (b), the impact of aluminum wall thickness on equivalent thermal conductivity coefficient shows approximately linear, the equivalent thermal conductivity coefficient of hollow-structure aluminum increases with the thickness of wall. Under the other conditions of non-changed parameters, with thickness for aluminum wall increasing, the proportion of aluminum alloy is heightened, the heat transfer of aluminum alloy is enlarged and the equivalent thermal conductivity coefficient is increased.
The influence of rib thickness (a) and cavity number (b) of hollow aluminum on equivalent thermal conductivity

It can be known from figure 4 (a), the impact of rib thickness on equivalent thermal conductivity coefficient of hollow-structure aluminum shows approximately linear, the equivalent thermal conductivity coefficient increases with the thickness of rib. Under the other conditions of non-changed parameters, with thickness for rib thickness increasing, it not only increases the proportion of aluminum alloy, but also it makes more heating transfer with the aluminum alloy in accordance with the principle of thermal-conduction resistance. On the whole, it makes the speed rate of equivalent thermal conductivity coefficient larger than the wall thickness of figure 3 (b) on its impacts.

It can be known from figure 4 (b), equivalent thermal conductivity coefficient increases with the number of cavities. There is little study on this aspect, which predicts that the interaction and composition between cavity leads to the increase of equivalent thermal conductivity coefficient while the number of cavities increases the proportion of aluminum alloy in the middle of total ingredient. The superimposed impact on these two reasons make hollow amount more obvious on heat transfer.

4. Conclusion and Prospect
1. With the change of load temperature on both sides of the hollow aluminum, the equivalent thermal conductivity keeps almost constant, it shows the natural convection in the cavity is very weak.
2. The number of cavities and rib thickness are the main factors that affect the heat transfer performance of hollow-structure aluminum. Wall thickness and temperature difference have limited influence on heat transfer performance.
3. Reasonable structure parameters should in accordance with specific conditions of the train in the actual engineering application, such as strength and load bearing, to reduce the energy consumption of train.

5. References
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