Pass design and thermal analysis of high thermal resistance multi-row sintered bricks

W Jiang¹,², D Liu³, Z H Yang¹,²
¹ Key Laboratory of Advanced Civil Engineering Materials (Tongji University), Ministry of Education, 4800 Cao’an Road, Shanghai 201804, China
² School of Materials Science and Engineering, Tongji University, 4800 Cao’an Road, Shanghai 201804, China
E-mail addresses: jiangwei@tongji.edu.cn (W Jiang); 1730592@tongji.edu.cn (D Liu); yzh@tongji.edu.cn (Z H Yang)

Abstract. In the thermal analysis, a numerical calculation method to verify the steady heat transfer coefficient of multi-row bricks was obtained. The effects of thermal conductivity, the number of rows and holes, the ratio of transverse wall area to wall rib area were analyzed with a view to finishing the optimal pass design for the 240 thick high thermal resistance of multi-row bricks. And the influence laws of heat transfer change of multi-row bricks were probed both in the steady state and unsteady state.

1. Introduction
With the developing of society and the upgrading of energy-saving technology requirement, buildings has contributed over 40% of the global energy consumption[1], and the thermal performance of sintered wall has been difficult to meet the increasing demand of energy saving and emission reduction. Building insulation technology, as one of the key technologies in building energy-saving, the contradiction between thermal retention and strength still exists in reality[2]. That is, starting from the optimization of sintered wall structure itself, analysis and research on the improvement of thermal performance of envelope structure and energy-saving building insulation technology, are of great significance to the sustainable development of society economy.

The development of sintered brick has experienced solid brick, porous brick, hollow brick and so on. The study [3-4] shows that the thermal insulation of hollow brick is better than that of solid brick, and the strip hole is better than the circular one. The larger the porosity (the more the number of holes), the smaller the thermal conductivity is. At present, the pass design of the mainstream brick type is not reasonable enough, there are some problems such as the through heat bridge, the heat transfer coefficient is too large [5], and the heat transfer analysis under the unsteady condition are few [6]. Therefore, it is the direction of future development to meet the requirements of large porosity, high thermal resistance and excellent mechanical properties of sintered wall materials.

In this paper, the 240 high thermal resistance multi-row sintered bricks with thermal properties were studied by numerical calculation and its influencing factors were analyzed. It is of great practical significance to guide the pass design of self-insulating wall materials, optimize the research methods of thermal properties and the application of energy-saving production.
2. Numerical calculation method of heat transfer

2.1. Introduction to steady-state numerical calculation of heat transfer

The heat transfer coefficient of wall parts is defined as the heat transfer per unit of time through the unit area when the temperature difference between the two sides of the enclosure is 1 degree (K or ℃) under the condition of steady-state heat transfer[7]. Therefore, when simulated heat transfer in ABAQUS, the multi-row hole model of 400mm × 240mm is established with shell element. The parameters of filling material and wall rib material are set up in table 1 below, and the boundary conditions are ±0.5 ℃ above and below, respectively. The time step is set to 172800s (at which time the heat transfer has reached steady state), and the grid is 0.001m to ensure the uniform partition of the model, computational convergence, and the field definition of the output NT. Finally, the heat transfer coefficient of wall parts can be obtained by using the temperature of 11 nodes and the heat flux of HFL element.

Table 1. Setting parameters of wall ribbed and filling materials.

| Material          | Density (kg·m⁻³) | Coefficient of heat conductivity (W·m⁻¹·K⁻¹) | Specific heat (J·kg⁻¹·℃⁻¹) |
|-------------------|------------------|---------------------------------------------|-----------------------------|
| Wall ribbed material | 1100             | 0.30                                        | 1050                        |
| Filling material  | 30               | 0.03                                        | 1380                        |

2.2. Experimental verification

2.2.1 Laboratory testing of the actual heat transfer coefficient of the wall. In this paper, the wall heat transfer coefficient of ceramic foam concrete lightweight bricks was measured. Figure 1 (a) is the structure of the system used to measure the steady-state heat transfer performance. Figure 1 (b)-(c) shows the experimental masonry wall and masonry respectively. The interior point of figure 1 (b) intermediate frame is the temperature measurement point [8]. The heat transfer coefficient (stage I) was measured at 20 ±5 ℃, 30 ±10 % relative humidity and 28 days in the environment after completion of masonry. After the measurement was completed, the wall was close to the hot box side with 2 cm ordinary plaster mortar, cured in the same environment for 28 days, and its heat transfer coefficient (stage II) was measured. Then, 2 cm thermal insulation mortar to the wall near the cold box was applied and its heat transfer coefficient (stage III) was measured after 28 days of maintenance. The experimental results of heat transfer coefficient K of three groups of walls have been obtained through three different stages of cold-hot surface temperature test (table 2).

![Figure 1. Test masonry and measuring system.](image)

Table 2. Test results of heat transfer coefficient and thermal resistance of wall.

| Stage | Q₁ value (W) | Hot surface temperature (℃) | Cold surface temperature (℃) | R value (m²·K·W⁻¹) | K value (W·m⁻²·K⁻¹) |
|-------|--------------|-----------------------------|-------------------------------|---------------------|---------------------|
| I     | 81.981       | 20.6                        | -15.9                        | 0.445               | 1.854               |
| II    | 63.583       | 19.2                        | -11.3                        | 0.480               | 1.660               |
| III   | 37.121       | 21.4                        | -7.3                         | 0.773               | 1.060               |
In addition, according to the heat transfer coefficient formula of "Code for Thermal Design of Civil Buildings" [7] (GB50176-2016), the analytical values of three groups of wall heat transfer coefficient K are obtained (table 2).

### 2.2.2 Numerical simulation

The heat transfer coefficient (thermal resistance) of the ceramic foam concrete lightweight bricks is calculated according to the numerical calculation method of the wall heat transfer coefficient, which is aimed at verifying the feasibility and accuracy of the numerical calculation. The actual model is divided into three kinds with the laboratory. Different interactions are added at both ends of masonry as hot surface temperature and cold surface temperature, respectively. The three-stage K value simulation results are shown as table 3.

| Stage | Simulated numerical value (W·m⁻²·K⁻¹) | Code formula analytic value (W·m⁻²·K⁻¹) | Deviation from analytic value A (%) | Test measured value (W·m⁻²·K⁻¹) | Deviation from measured value B (%) |
|-------|---------------------------------------|----------------------------------------|-----------------------------------|-------------------------------|-----------------------------------|
| I     | 1.726                                 | 1.763                                  | -2.10                             | 1.854                         | -6.90                             |
| II    | 1.672                                 | 1.644                                  | +1.70                             | 1.660                         | +0.72                             |
| III   | 1.164                                 | 1.169                                  | -0.43                             | 1.060                         | +9.81                             |

Using the formula relative error value = (simulated numerical value - reference value) / reference value × 100%, respectively, the analytic value and the experimental measured value are the reference values, and the two sets of relative error differences A and B are obtained as shown in table 3. The relative error between the numerical value and the analytic value of the code formula does not exceed 2.1%, and the relative error between the simulated numerical value and the experimental measured value does not exceed 10%. Numerical calculation of wall heat transfer coefficient is feasible and effective. The simulated numerical value is close to the experimental measured value and the analytic value of the code formula.

### 3. Heat transfer optimization design

#### 3.1. Design of three, four and five rows of holes and results of heat transfer

Aimed at achieving the heat transfer coefficient 0.3W/(m²·K) 240mm thick high thermal resistance porous sintered bricks, a three-row porous brick was designed. In order to reduce the machining difficulty and the mechanical strength of sintered bricks, the structure optimization of the initial three-row hole scheme is carried out. Firstly, the porosity ratio is kept ≥ 60% in the hole optimization design, and all the standard holes and side holes are kept consistent as far as possible in order to reduce the machining difficulty and the need of mechanical strength of sintered bricks. According to table 4.2.1 of GB50574-2010 Uniform Technical Code for the Application of Wall Materials, the wall thickness and rib width of perforated brick for self-supporting wall are all ≥ 10 mm[9]. After a comprehensive comparison, the final design of three optimal hole types of three to five rows are shown in figure 2 (a) (b) (c) and table 3 below. (In order to achieve the goal of low heat transfer coefficient, a small portion of the rib width of the sintered bricks exceeds the requirements of the existing specifications mentioned above. The corresponding production process is stepping up research and development.)

![Figure 2. Diagram of three/four/five-row hole’s design.](image-url)
Table 4. Optimal design of three-row, four-row and five-row hole. (mm)

| General dimension | Hole height | Standard hole width | Side hole width | Vertical rib width | Transverse wall thickness | Porosity rate (%) |
|-------------------|-------------|---------------------|-----------------|-------------------|--------------------------|------------------|
| Width             | Thickness   | 57                  | 80              | 46                | 16                       | 17               | 18.5          | 56.53         |
| Original          | 400         | 245                 | 46              | 17                | 13.5                     | 66.78            |
| 3-row             | 400         | 240                 | 62              | 85                | 12                       | 11.5             | 13.5          | 66.78         |
| 4-row             | 400         | 240                 | 47.5            | 89                | 10                       | 8                | 12            | 70.46         |
| 5-row             | 400         | 240                 | 36              | 68                | 10                       | 12               | 10            | 63.75         |

When simulating heat transfer in ABAQUS, the multi-row hole model of 400mm × 240mm is established. The size of the model is shown in table 4. The thermal conductivity of filling material (foamed polyurethane) and wall rib material (lightweight concrete) are 0.03W/(m·K) and 0.30W/(m·K), respectively. The time step is set to 172800s (at which point the heat transfer has reached steady state), the grid is 0.001m to keep the model partition uniform and the calculation convergence. The field definition outputs the NT11 node temperature and the heat flux value of the HFL element. The heat transfer coefficient of wall parts can be obtained finally.

The results show that the heat transfer coefficient of three-row model is 0.303W/(m²·K), and that of four-row model is 0.268W/(m²·K), which is 11.52% lower than that of three-row hole. The optimum heat transfer coefficient of the five-row hole model is 0.174W/(m²·K), which is 42.57% lower than that of the three-row hole heat transfer coefficient. In order to satisfy the porosity ≥ 60%, keep the edge angle easy to form and not easy to break, and satisfy the heat transfer coefficient ≤ 0.3W/(m²·K), it can be concluded that the five-row hole design is the optimal hole type in terms of thermal properties.

It can be seen from the heat flux distribution map of multi-row holes that the heat flux density in the part of the filling material is small, but the heat flux density in the wall rib is higher, so it is easy to form the heat bridge. The heat flow of the wall rib should be reduced by increasing the hole ratio and avoiding the penetration of the heat bridge. The heat flow distribution diagram of the five-row holes is shown in figure 3, and the overall heat flow value (compared with the three-four holes) is decreased, which is shown in the reduction of the heat transfer coefficient mentioned above, and the advantage of the five-row holes is more obvious.

Figure 3. Distribution of heat flux in five-row hole.

3.2. Influence of heat transfer on steady state

In addition to optimizing the internal pass design of sintered bricks, the influence factors of heat transfer coefficient under the steady state were studied. Firstly, the relationship between the heat transfer coefficient and the thermal conductivity of the wall rib material and the filling material is investigated by changing the material types such as the following table 5 for the same hole structure (three-row hole).

Table 5. Results of simulated heat transfer coefficient with three-row hole.
No. & Thermal conductivity of filling materials (W·m⁻¹·K⁻¹) & Thermal conductivity of wall ribbed materials (W·m⁻¹·K⁻¹) & Integral heat transfer coefficient (W·m²·K⁻¹) \\
1 & 0.030 & 0.30 & 0.303 \\
2 & 0.040 & 0.30 & 0.335 \\
3 & 0.042 & 0.30 & 0.344 \\
4 & 0.042 & 0.35 & 0.375 \\
5 & 0.042 & 0.42 & 0.417 \\
6 & 0.058 & 0.42 & 0.469 \\

It is concluded from table 5 that the heat transfer coefficient decreases with the decrease of the thermal conductivity of the filling material and the wall rib material. When the thermal conductivity of filling material is 0.030W/(m·K), wall rib material is 0.30W/(m·K), the overall heat transfer coefficient is the smallest. That is, its overall thermal resistance is the largest, heat transfer performance is the best.

Secondly, unifying hole rate 63.75%, changing the thickness of transverse wall from 6~14mm as shown in table 6, and exploring the relationship between the heat transfer coefficient of five-row holes and the thickness of transverse wall. As can be seen from table 6 and figure 4 (a) (b), when the uniform porosity is 63.75% in steady-state condition, the heat flux through wall rib becomes less and less with the increase of transverse wall area / wall rib area. At the same time, the heat flux through the wall rib is less and less, the heat transfer coefficient is positively correlated with the heat flow through the wall rib, and the heat transfer coefficient becomes smaller and smaller. The larger the thermal resistance is, the better the thermal insulation performance is.

Table 6. Results of simulated heat transfer coefficient with five-row hole.

| Transverse wall height (mm) | Vertical rib width (1/3/5) (mm) | Vertical rib width (2/4) (mm) | Transverse wall / wall rib (%) | Wall rib heat flux ratio (%) | K value (W·m²·K⁻¹) | Porosity rate (%) |
|----------------------------|---------------------------------|--------------------------------|-------------------------------|------------------------------|-------------------|------------------|
| 6                          | 16.67                           | 20.00                          | 41.4                          | 75.00                       | 0.35              | 63.75            |
| 8                          | 13.54                           | 16.25                          | 55.2                          | 74.05                       | 0.34              | 63.75            |
| 10                         | 10.00                           | 12.00                          | 69.0                          | 67.66                       | 0.32              | 63.75            |
| 12                         | 5.95                            | 7.14                           | 82.8                          | 63.15                       | 0.27              | 63.75            |
| 14                         | 1.28                            | 1.54                           | 96.6                          | 43.90                       | 0.20              | 63.75            |

Figure 4. Influencing factors of heat transfer coefficient under steady state.
3.3. Influence of heat transfer on unsteady state

First of all, in the same unsteady (periodic unsteady) outer environment, the influence of 3, 4, 5 rows of holes on the heat flux distribution and temperature distribution on the inner side of multi-row brick is investigated. The three basic models are the same as text 2.2.. All of them only change from constant temperature to periodic sine function for the outside temperature $T(t)$ of multi-row holes. Of which $T$ is the outside temperature working time, the inner temperature $T(t)$ is set as the free temperature boundary, only the initial temperature value is set; the analysis step is set to 129600 s (1.5 days).

The final results of the numerical simulation are shown in figure 5 (a) (b). The non-steady-state outside temperature variation function of the three types of holes is the same in figure 5 (a). With the increase of time, the inside transient heat flux curves are sinusoidal, and with the increase of the number of holes, the transient heat flux curves are sinusoidal. The variation trend of the transient heat flux sine function curve of the three, four and five rows of holes is more smooth, and the minimum value is smaller.

In figure 5 (b), the transient temperature curves on the inside side of the three types of holes increase step-by-step with the increase of time, but the change of the transient temperature of the inner side of the four-and five-row holes is obviously smaller than that of the three-row holes all the time. Relatively speaking, the internal transient temperature change of the five-row hole is the smallest. Therefore, with the increase of the number of holes, the smaller the influence of the external heat transfer on the inside transient heat flux and the transient temperature is, the better the thermal insulation performance is.

![Figure 5](image_url)

Secondly, when the steady-state thermal resistance is the same, the influence of non-steady-state outside environment change on the transient heat transfer of solid brick and hollow brick is investigated. Keep the steady-state thermal resistance of the two types of bricks unchanged, and set the same external temperature unsteady-state variation function as above, as shown in figure 6 (a) (b).

Figure 6 (a) shows that the transient heat flux temperature values of solid brick and hollow brick are different from that of hollow brick in unsteady external environment when the steady-state thermal resistance of wall material is the same. The inside transient heat flux of solid brick is more sensitive to the unsteady change of temperature than that of hollow brick. The inside transient heat flux curve is sinusoidal and the peak value is higher and the valley value is lower. The hollow brick is relatively stable and has a certain time lag. Figure 6 (b) shows that the overall trend of temperature change of solid brick increases rapidly, which is higher than that of porous hollow brick. When the steady-state thermal resistance of the wall is the same, the transient heat flux and the transient temperature of the porous hollow brick in the unsteady outer environment are different from that of the solid brick. The divergence is smaller, the change is more stable, and the heat preservation performance is better.
4. Conclusions

Under the same parameter setting, the simulated numerical value is close to the experimental data and the analytical value of the code formula, so the numerical calculation of wall heat transfer coefficient under steady state is feasible and effective.

(1) In steady-state environment, when the porosity is kept above 60%, with the increase of the number of rows and holes, the heat transfer coefficient decreases obviously. When the number of holes is same and the ratio of holes are all 63.75%, with the increase of transverse wall area / wall rib area, the heat flux through the wall rib becomes less and less, the heat transfer coefficient is positively correlated with the heat flow through the wall rib, and the heat transfer coefficient becomes much smaller. And the larger the heat resistance is, the better the insulation performance is.

(2) Under the condition of unsteady-state environment (periodic unstable state), with the increase of the number of rows and holes, the less the influence of the heat transfer on the outside is, the heat preservation performance is better, and the transient heat flux and the transient temperature are less affected by the outside heat transfer. When the steady-state thermal resistance of the wall is the same, the transient heat flux and transient temperature change of the porous hollow brick in the unsteady outer environment is smaller than that of the solid brick, the change is more stable and the thermal insulation performance is better.

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