CHEMICAL ENGINEERING TRANSACTIONS

VOL. 51, 2016

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Tichun Wang, Hongyang Zhang, Lei Tian

ISBN 978-88-95608-43-3; **ISSN** 2283-9216

DOI: 10.3303/CET1651198

Analysis on Thermal Performance of Composite Wall of Energy-saving Buildings

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3D temperature field and thermal resistance of new energy-saving wall blocks are calculated with finite difference method in order to save land resources and reduce the engineering cost of the main structure of buildings, and the equivalent thermal conductivity coefficient is connected with the thickness of air layer in the calculation to make the calculation results more accurately reflect the thermal performance of wall blocks. Many factors affecting the thermal resistance of blocks such as heat transfer coefficient, delay time are analyzed in this paper, and many methods for the improvement of thermal resistance of wall blocks are put forward. It is shown in the research that new composite walls have good effects on the winter and the summer, and its thermal stability and indoor comfort are increased significantly compared with traditional non energy-saving walls.

1. Introduction

With the development of the construction, the demand for wall materials is increasingly growing. At present, more than 80% of the wall materials are still solid clay bricks in China, and the production mode for this kind of wall materials is basically the excavation of earth on the spot, which is easy to destroy cultivated land, waste energies and pollute environment (Ai et al, 2009). Recently, the State Economic and Trade Commission has determined that 170 cities are prohibited to use solid clay bricks 2 years later, and other provincial cities will be prohibited to use solid clay bricks by the end of 2005. In addition, our country has formulated Building Thermal of Residential Building and Design Standard for Heating and Energy-saving to put forward the requirements for 50% energy saving on the heat preservation and heat insulation of building palisade structure (Susorova et al, 2013). Doing well in the innovation of wall materials and the energy saving of residential buildings are not only the needs of the development of the building material industry and construction industry themselves, but also the objective requirement of national economy and social development (Zhang et al, 2012).

Table 1: The basic structure of the wall

Building type	number	Wall materials	The wall structure
General construction	1	240 Clay bricks	240 Clay bricks + 20 cement plaster
	2	370 Clay bricks	370 Clay bricks + 20 cement plaster
After energy-saving renovation of buildings	3	370 Clay brick exterior insulation	6 Cement plaster external protection+50polystyrene+20clay brick
New energy saving building	4	240 Clay brick exterior insulation	6 Cement plaster external protection+50polystyrene+20clay brick
	5	240 Clay brick interior insulation	6 Cement plaster external protection+50polystyrene+20clay brick
	6	240 Clay porous brick exterior insulation	6 Cement plaster external protection+ 50polystyrene +20 clay porous brick

Please cite this article as: Hu Y.L., 2016, Analysis on thermal performance of composite wall of energy-saving buildings, Chemical Engineering Transactions, 51, 1183-1188 DOI:10.3303/CET1651198

2. Basic Types of Wall Body

At present the basic construction of retaining wall structure can be divided into three types: (1) non energy-saving buildings built in 50s～80s in 20th century; (2) energy-saving buildings reconstructed from the existing buildings with exterior wall thermal insulation technology; (3) energy-saving buildings built according to the wall materials innovation and building energy-saving standard. The basic structures of the wall above are shown in Table 1 (The wall numbers in the paper are subject to this), and the thermal physical property indexes of wall materials are shown in Table 2 (Wang and Shen, 2011).

Table 2: Wall material thermal physical property indexes

Material	Density ρ/(kg·m^{-3})	Specific heat C/(kJ·(kg·℃)$^{-1}$)	heat conductivity coefficient λ/(W·(m·℃)$^{-1}$)	24H heat storage coefficient S/(W·(m2·℃)$^{-1}$)
Ash brick masonry sand	1900	1.05	1.1	12.72
Clay solid brick masonry	1800	1.06	0.8	10.63
Slag brick masonry	1750	1.05	0.8	10.43
Porous brick masonry	1480	1.06	0.58	7.92
Cement mortar	1850	1.05	0.93	11.37
polystyrene	40	1.07	0.04	0.48

3. New and Energy-saving Composite Wall Block

Self-thermal insulation system is a kind of wall thermal insulation system collected with structure and function, the thermal insulation materials used for such kind of walls are the materials of walls, and the materials of the wall itself is the concrete block for the self-thermal insulation concrete block wall(Pop et.al, 2006), in order to improve the thermal insulation property of concrete block wall so as to make the new wall structure satisfy the requirements for the corresponding energy saving standard, the chain type concrete block developed by the author is "∴"-type block, the base materials for the shell of the block uses lightweight aggregate concrete, and the insulation materials are filled in the holes so that it is called chain type self-thermal insulation concrete block (Terekhov et al, 2005).

3.1 Geometry structure of new energy-saving composite wall block

The external structure size of chain type self-thermal insulation block is 390mm*250mm*190mm, with the width of its internal filling holes of 70mm (Massouros et al, 2000), middle air layer of 12mm, and the intermediate rib on both sides of the shell of 25mm, and the detailed drawing of the outside of the block is as shown in Figure 1,

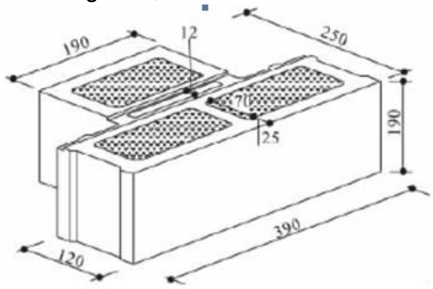

Figure 1: Sketch map of concrete block

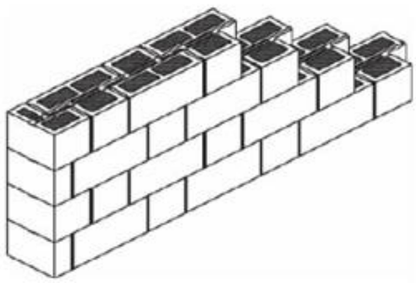

Figure 2: Sketch map of 250mm wall

The chain type self-thermal insulation concrete block wall uses the laying of upper and lower staggered joints, with the staggered joints of 100mm and inner and outer plastering of 25mm(Kossecka, 1999), and its structure type is as shown in Figure. 2,

3.2 Analysis on the thermal unit of new energy-saving composite wall block

The temperature of inner surface and outer surface of the wall remain stable in the process of steady-state heat transfer, when the width and height of the wall body are much bigger than its thickness, it can be approximately thought that wall temperature changes only along the thickness direction, namely heat flow only flows along the thickness direction, so the steady-state heat transfer of the wall can be analyzed as approximately one dimensional steady-state heat transfer. In view of this, the unit with cyclical changes in the longitudinal section is selected as the thermal performance analysis unit according to the wall structure, as is shown in Figure 3 (Bansal and Chin, 2012)

Numerical simulation of thermal performance is mainly carried out on the thermal analysis unit shown in the diagram above to compare and analyze the distribution of inner temperature field and heat flux density field of the unfilled block wall and filled block wall, and the wall heat transfer coefficient of the two walls is calculated.

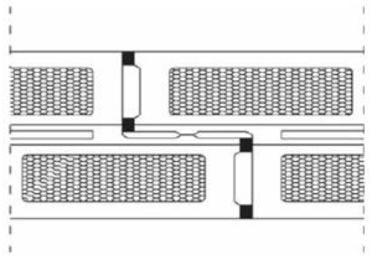

Figure 3: Thermal analysis unit of wall

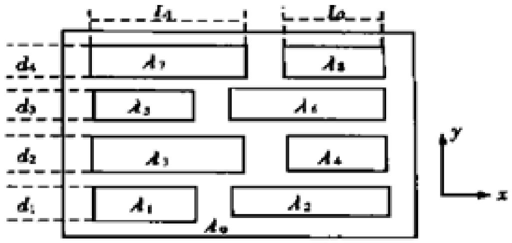

Figure 4: Physical model of wall Block

4. Mathematical Model of Thermal Analysis and Physical Model

4.1 Thermal Conductivity Coefficient of Air Equivalent

The holes of the current hollow wall block are mainly round, square and rectangle. In the case of the same hole rate, rectangle holes are best in terms of increasing thermal resistance of wall block. The simplified physical model used for the calculation of the wall block in this paper is as shown in Figure 4, with the rectangular holes of the block arranged staggered.

In figure 4 λ_0 indicates the coefficient of thermal conductivity of wall brick aggregate, $\lambda_1 \sim \lambda_8$ represent the thermal conductivity coefficient of air equivalent in the holes. In Figure 1, give different values to $\lambda_1 \sim \lambda_8$, concrete hollow wall block with different structure and different holes can be obtained. The heat transfer situation of the air in the holes in figure 4 has a direct effect on temperature distribution in the wall block. It is not satisfactory that some literatures process the thermal conductivity coefficient of air in the holes of the wall blocks as a constant. In fact, the thermal conductivity coefficient of air layer has something to do with the hole width and hole height. Based on literature, thermal conductivity coefficient of air layer equivalent λe can be calculated with formula (1) (Burek and Habeb, 2007).

$$\lambda_c \bar{\lambda} = c(Gr_d\, p_r)^m (dlh)^n \tag{1}$$

Equation: λ is the thermal conductivity coefficient of air, W/(m℃); C, m and n are coefficients; Gr_d is the air Grasholf Number; P_r is the Prandtl Number; d is the hole width, m; h is the hole height, m. The calculation results of formula (1) accord with the reference values proposed in civil design manual, which indicates that formula (1) is reliable.

4.2 Mathematical Model of Heat Transfer of Wall Block

In order to calculate conveniently thermal resistance of new wall block shown in Figure 1, considering the calculation unit is just one part of the wall, so it is supposed that the upper, lower, right and left sides of the calculation unit are the boundary condition of thermal insulation, and the differential equations used for the calculation of unit thermal conductivity is shown as formula (2):

$$\frac{\partial}{\partial x}\left[\lambda x \frac{\partial t}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda y \frac{\partial t}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda z \frac{\partial t}{\partial z}\right] = 0 \tag{2}$$

Boundary condition:

$$\begin{cases} t\,|_{y=0} = t_{1,} t\,|_{y=d} = t_2 \\ -\lambda x \dfrac{\partial t}{\partial x}\,|_{x=0} = 0, -\lambda x \dfrac{\partial t}{\partial x}\,|_{x=L} = 0 \\ -\lambda x \dfrac{\partial t}{\partial z}\,|_{z=0} = 0, -\lambda x \dfrac{\partial t}{\partial z}\,|_{z=h} = 0 \end{cases} \tag{3}$$

For the equation mentioned above, finite difference method is used in this paper to calculate temperature field, and the wall block thermal resistance is calculated with heat flow.

5. Analysis on calculation results

5.1 Comparison between calculated value and the test value

Compare the calculation of 390mm×190mm×190mm wall block with the test results in literature, and the results are shown in Table 3:

Table 3: Contrast calculation and test result

Row number	Heat conductivity coefficient $\lambda/(W\cdot(m\cdot°C)^{-1})$	Long hole/ hole width	Thermal resistance $R/(m^2\cdot°C)\ W^{-1}$		Error (%)
			Calculated	Tested	
A row of holes	0.6	290*90	0.354	0.356	0.62
	1.50	290*90	0.198	0.214	5.8
	0.35	290*90	0.568	0.542	1.8
Two rows of holes	0.32	290*90	0.734	0.783	2.1

It can be known from the data in the table that calculation value and test value are close, with the maximum error of 5.7%. It shows that calculation results in this paper can well reflect the thermal characteristics of wall block.

5.2 The influence factors of thermal resistance of composite wall block

(1) The influence of the number of hole rows on block thermal resistance

The average thermal conductivity coefficient of exterior wall k≤1.5W /(m℃), and considering the thermal resistance of beams and columns is small, the wall thermal resistance must be improved in order to achieve the purpose of 50% energy saving; according to the calculation, the thermal resistance of 240mm thick new concrete hollow wall block should be up to 0.70m^2℃/W. so large amounts of calculation is made on the blocks with cement with the thermal conductivity coefficient of 0.79 w/(m℃) as an aggregate, and it can be found from the results that the hole size and the number of hole rows have certain influence on the thermal resistance of block. Figure 2 is the relation curve of hole width, block heat resistance R and the number of hole rows for 380mm×240mm×200mm block with the hole rate of 46% and the hole length of 110mm+ 170mm.

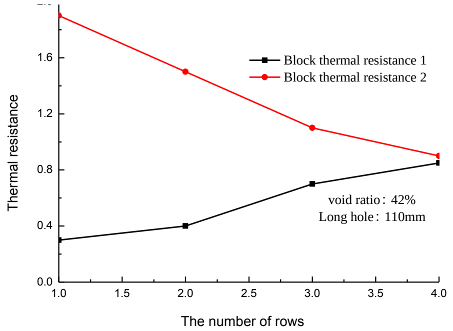

Figure 5: Relation curve of hole width, block heat resistance r and the number of hole rows

It shows from figure 5 that with the increase of the number of hole rows, hole width gradually decreases to cause the weakening of convective heat transfer and the declining of thermal conductivity coefficient of air layer equivalent so that the wall block thermal resistance is increased. Compare 4 row of holes with one row holes in figure 4, the thermal resistance of block will increase by 162% if the width of each row of holes is decreased by 75%. This fully shows that hole rows of wall block has remarkable effects on the thermal resistance. So under the condition of guaranteeing wall block strength and process, try to use multiple rows of blocks as far as possible. The thermal resistance of block with structure of 3 and 4 rows of holes in figure 5 is higher than 0.70 m^2℃/W, which conforms to the requirements of the energy saving; and the thermal resistance of block with structure 1 and 2 rows of holes is lower than 0.70 m^2℃/W, which fail to meet the requirements of energy saving. For different sizes of blocks, as long as the hole rate and the hole length are certain, the trend of the influence of the number of hole rows on the hole width and thermal resistance of blocks is all shown as figure 5.

(2) The influence of the hole staggered extent on block thermal resistance

The rate of the length of long and short holes in figure 4 can represent the hole staggered degree, when hole rate is consistent with hole width, the influence of hole staggered degree on the thermal insulation of wall block is shown in figure 6, and the block in figure 6 is 380mm×240mm×200mm.

In figure 6, $L_1/L_2=1$ stands for holes are arranged neatly, and the thermal resistance of wall block is minimum. With the increase of L_1 / L_2 and the aggravating of holes staggered degree, the block thermal resistance is increased. After L_1 / L_2 = 7 ~ 10, block heat resistance is almost the same. In figure 6, the differences between the maximum and the minimum of thermal resistance are respectively 6.8% and 8.5% for 3 row holes and 4 row holes block. And it is found by computing the results that: in general, if the neat arrangement of holes is changed to staggered arrangement, the increase of block thermal resistance will be no more than 10%.

(3) The influence of different hole width for multiple rows holes on the thermal resistance of block

Figure 7 is the relation curve of the thermal resistance of block and hole width of 380mm×240mm×200mm wall block, with the hole rate of 43%, the hole length of 70mm + 210mm under the condition of two rows of holes. The transverse coordinate in figure 7 is the outer hole width of two-row holes middle wall, because the hole rate, number of hole rows and hole length of each row are not changed, the sum of width for two-row in this case is 140mm. The curve for not filling materials is three zones, one row holes in the two-row holes in I and III zone is larger than 80mm in hole width, and the hole width of another row is less than 60mm. The difference between the width of wide holes and narrow holes is greater, the thermal resistance of blocks is smaller. Compared to I and III zones, the thermal resistance of blocks in II zone is much smaller, which is because the hole width of two row in II zone is greater than 60mm, and it is known according to the literature: the heat release of air in two rows of holes belong to infinite space free flow heat release, the equivalent thermal conductivity is very big and the thermal resistance of block is lower naturally. When hole width is less than 60mm, the air convective heat transfer is weak and the equivalent thermal conductivity is very small, so block heat resistance has a higher degree of rise in the two curves in the figure 4, with hole width of 80 mm at the external wall and 60mm at the internal wall. It needs to attention when determining the hole size: if holes are not filled with materials, the hole width of each row shall not be different greatly, and the phenomenon that too many hole width is larger than 60mm shall be avoided. For example, the thermal resistance with hole of 70mm + 70mm in figure 4 is less than that of block with hole of 60 mm + 80 mm.

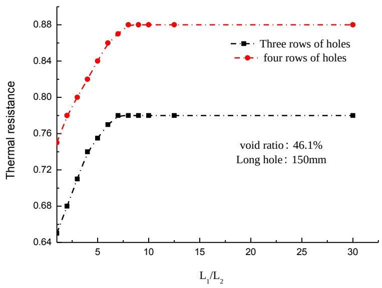

Figure 6: The hole distance to block the effects of thermal resistance

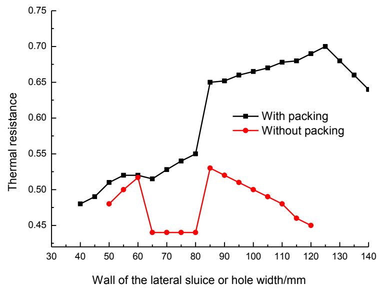

Figure 7: The hole width to add filler block the effects of thermal resistance

(4) The influence of stuffing materials on the thermal resistance of block

For the wall blocks with a small number of hole rows, in addition to the change of wide holes into narrow holes and the increase of the number of hole rows, sometimes this aim can be achieved by adding insulation materials so as to significantly improve the block thermal resistance. The dotted line in figure 7 represents the thermal resistance of block added into the outer holes with polystyrene stuffing materials with the thermal conductivity ofλ=0.129W /(m℃). It can be known from this curve that block thermal resistance increases with the increase of outer hole width and the thickening of stuffing materials. This is because the stuffing materials thickens and the hole width inside becomes smaller, and the thermal conductivity coefficient of air equivalent decreases. When the stuffing materials is 126 mm thick, the air layer is 14 mm wide and G_{rd}<2 000, the air heat transfer is conducted according to pure thermal conduction method, and the block thermal resistance increases to the maximum of 0.704m^2℃/W. Later, air thermal conductivity coefficient doesn't change any longer, and block thermal resistance decreases along with the increase of the thickness of stuffing materials.

6. Conclusion

The calculation program prepared in this paper for the calculation of three dimensional temperature field and thermal resistance of new type wall block has a certain universality. Due to the consideration of the effect of the thickness of air layer on the thermal conductivity of air layer equivalent, the calculated results can more accurately reflect the heat transfer characteristic of new wall block. Through the calculation, there are the following methods for the improvement of wall block thermal resistance and the enhancing of its thermal performance:

(1) Use rectangular holes of staggered arrangement, improve the ratio of the length of long and short holes, but after L_1/L_2= 7～10, it is meaningless to improve the staggered degree of long and short holes. Change the hole arrangement mode from neat arrangement to staggered arrangement, the increase amount of thermal resistance of blocks will not exceed 10%.

(2) In the circumstances of the same hole rate, changing wide holes to narrow holes and increasing the number of hole rows are the best for the improvement of the thermal resistance of walls.

(3) It shall pay great attention when determining the size of block's holes: if holes are not stuffed with materials, the hole width of each row holes shall not be great and the phenomenon that too many hole width is greater than 60mm shall be avoided.

(4) Proper stuffing of insulation materials for blocks with small number of hole rows is beneficial to the improvement of block heat resistance. The smaller the thermal conductivity coefficient of stuffing materials, the better, of course, this will increase the cost of the wall block. The less the hole rows, the larger the help of stuffing insulation materials to increase the heat preservation and insulation of walls.

(5) For the stuffed wall blocks with the same of hole rate and the number of hole rows, widening the thickness of the stuffing materials and reducing the thickness of air layer can further increase the wall block thermal resistance. But after the air layer is more than 14 mm, it is not proper to widen the thickness of stuffing materials, otherwise the wall block thermal resistance will be reduced, and the wall's capacity of heat preservation and insulation will be reduced.

Acknowledgments

This study is supported by China National Spark Program (No. 2015GA690045) and Building Systems Technology Project of Jiangsu Province (No. 2015ZD71).

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