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Effect of Aluminum on Thermal Performance of Ceramsite and its Application†

FANGLIANG LIU[1] and WEIWEI WU[2,*]

[1]College of Civil Engineering and Architecture, Harbin University of Science and Technology, Harbin 150080, P.R. China
[2]School of Management, Harbin Institute of Technology, Harbin 150001, P.R. China

*Corresponding author: Fax: +98 451 86414042; Tel: +86 13100875468; E-mail: wuweiwei@hit.edu.cn

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Thermal performance, such as the thermal resistance and thermal conductivity of ceramsite under the effect of aluminum, were measured. A holistic model was developed to measure the thermal performance. Different ceramsite insulation structures were selected for simulating and comparing. By simulating the holistic model, it was found that aluminum greatly promotes the thermal resistance of ceramsite to twice the thermal resistance of ceramsite. The average thermal conductivity of ceramsite under the effect of aluminum is decreased by 50 %. The marginal thermal resistance of the ceramsite insulation structure stuck on aluminum foil internally is almost the same as that of the widely used ceramsite hollow brick with EPS board and it is incombustible, which implies a better structure for architectural heat insulation.

Keywords: Ceramsite, Aluminium foil, Thermal performance, Cost performance.

INTRODUCTION

The ceramsite is a kind of good insulation material, which has disconnected honeycomb micropore to insulate water and keep air inside. The ceramsite is usually used to make hollow bricks with the air layer inside, which greatly promote its thermal performance[1,2]. For better thermal performance, new materials and methods are tested and developed. For example, Lee and Peesiki[3,4] fills the hollow ceramic insulation material with expanded polystyrene (EPS) board inside, while Sun & Fang[5] and Aiad *et al.*[6] put the EPS board outside. However, previous research lacks the consideration of the economical efficiency, which limits the application of those new materials and methods. The methodology of analyzing the thermal performance applied in previous research mainly includes experimentation[7,8], theoretical computation and numerical simulation. However, the experimentation requires a large amount of human power, materials and financial resources and is usually a time consuming process. The theoretical computation mainly applies Homayr model[9,10], the model of American Society of Heating, Refrigerating and Air-Conditioning Engineers Handbook and the Thermal Design Code for Civil Building Manual model in China. These models are suitable for calculating the approximate value in a simple case, but unable to show visually the distribution of the temperature and heat flux inside the material. The numerical simulation focuses in simulating the complex heat transfer problems by computers. For instance, the HEAT2[11] and HEAT3 programs[12] by Lund University and Massachusetts Institute of Technology are developed to deal with two-dimensional and three-dimensional thermal issues. They are very good at analyzing the local temperature and heat flux of the material in a dynamic condition. However, this method is based on the decomposition of the material, which makes the model construction very complex. It cannot either explain the change of the overall properties of the material.

Thus, it is a need to develop a new insulation material with the value of application innovation and to develop a simple and effective method to analyze its thermal performance. The aluminum can reduce the heat radiation and is an economic material[13,14]. Therefore this work explores the effects of the aluminum on the thermal performance of the ceramsite insulation material in this paper. A holistic model is developed first. Then it is applied to analyze the thermal performance of a new ceramsite-foil insulations material. The value of the application innovation of the new material is analyzed in the final part.

EXPERIMENTAL

Model: A hollow ceramsite structure stuck on aluminum foil internally is considered herein, as depicted in Fig. 1.

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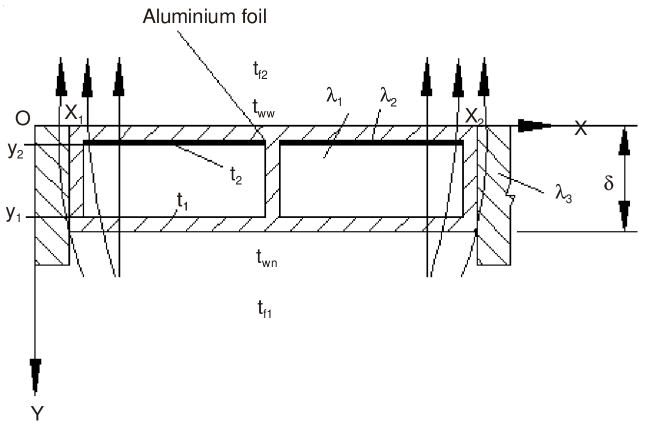

Fig. 1. Structure of hollow ceramsite insulation material

A holistic model is developed based on the first law of thermodynamics and the Fourier's law, which involves a series of equations. The thermal conduction differential equation, which correlates the temperatures of particles within an object with each other, is used to show the dynamics of the temperature (t) of the object[15,16].

$$\rho c\frac{\partial t}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial}{\partial z}\right)+\Phi \quad (1)$$

where ρ is the density of the material (kg/m^3); c is the material's specific heat capacity (J/(kg K)); λ is the thermal conductivity of material (W/(m K)); Φ is the heat caused by heating source in unit time of unit volume (W/m^3); z, y, z are spatial variables and τ is time variable.

In this model, the material has no internal heat source and is assumed as isotropic. Its thermo physical properties and boundary conditions do not change with the variation of temperature. Mass transfer, water vapor transmission and nonlinearity are negligible. The eqn. 1 can be given as

$$\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}+\frac{\partial^2 t}{\partial z^2}=\frac{\rho c}{\lambda}\frac{\partial t}{\partial \tau} \quad (2)$$

Taking the steady-state heat transfer into consideration, eqn. 2 become

$$\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}+\frac{\partial^2 t}{\partial z^2}=0 \quad (3)$$

The vertical temperature field can be regarded as fixed. The eqn. 4 can be written as:

$$\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}=0 \quad (4)$$

The boundary conditions of eqn. 4 are

$$-\lambda_1\frac{\partial t}{\partial y}|_{y=\delta_1}=\alpha_n(t_{f_1}-t_{wn}) \quad (5)$$

$$-\lambda_1\frac{\partial t}{\partial y}|_{y=0}=\alpha_w(t_{ww}-t_{f_2}) \quad (6)$$

$$-\lambda_1\frac{\partial t}{\partial x}|_{x=x_1}=\alpha_n(t_{f_1}-t_{wn}) \quad (7)$$

where λ_1 is the average thermal conductivity of the ceramsite (W/(m^2 K)); t_{f_1} is the temperature of the internal environment (ºC); t_{f_2} is the temperature of the external environment (ºC); t_{wn} is the temperature of the internal surface (ºC); t_{ww} is the temperature of the external surface (ºC); α_n is the convection heat transfer coefficient of the internal surface [W(m^2 K)]; α_w is the convection heat transfer coefficient of the external surface [W(m^2 K)].

The radiation can be expressed as

$$\lambda_2 A\frac{d^2T}{dy^2}\bigg|_{y=y_2}=\frac{(\varepsilon_2-J_1)}{\dfrac{1-\varepsilon_1}{\varepsilon_1 A}}+\alpha U(t_2-t_n) \quad (8)$$

where A is the area of the aluminum foil (m^2); λ_2 is the average thermal conductivity of aluminum [W/(m^2 K)]; ε_1 is the blackness of ceramsite; σ is the Boltzmann constant (5.67 × 10^{-8} W/(m^2 K^4)); t_1 is the radiation temperature of internal environment (ºC); t_2 is the temperature of the aluminum foil (ºC); U is the radiation heat exchange area (m^2); α is the convective heat transfer coefficient; t_n is the temperature of the inside air (ºC); J_1 is the radiation intensity of aluminum foil surface.

The eqns. 4-8 are the mathematical representation of the model. According to the principle of the thermal equilibrium[17,18],

$$Q_{Genreate}+Q_{Input}=Q_{Output} \quad (9)$$

where Q_{Input} is the influent heat (W/m^2), $Q_{Genreate}$ is the inside heat generation (W/m^2); Q_{Output} is the heat coming out (W/m^2). Substitute the variation forms of eqns. 4-8 into eqn. 9 to get the matrix expression of the thermal equilibrium equation as:

$$[C]\{\dot{T}\}+[K]\{T\}=\{Q\} \quad (10)$$

where [K] is the conductivity matrix, including thermal conductivity, the coefficient of convective heat transfer, emissivity and shape coefficient; [C] is the specific heat matrix; {T} is the temperature vector of nodes; { $\dot{T}$ } is the time derivative of the temperature; {Q} is the heat flux vector of nodes, including the heat generation.

RESULTS AND DISCUSSION

The holistic model is applied to measure the thermal resistance of the hollow ceramsite insulation structure with single-row core, the length of 390 mm, the width of 190 mm, the height of 190 mm, the hole width of 30 mm and the fin thickness of 20 mm. The model is run in ANSYS and the result is 0.361 m^2 ºC/W, which agrees with the actual value of 0.363 m^2 ºC/W. Thus the model is effective and reliable.

The model is then applied to measure the thermal resistance of the hollow ceramsite structure stuck on aluminum foil internally, with single-row core, the length of 390 mm, the width of 90 mm, the height of 190 mm, the hole width of 165 mm and the fin thickness of 20 mm. The average thermal conductivity of ceramsite λ_1 = 0.5 W/(m K) and the density is 1100 kg/m^3. The average thermal conductivity of aluminum foil λ_2 = 203.5 W/(m K). t_{f_1} is 18.06 ºC and t_{f_2} is -13.20 ºC. a_n and a_w are 8.7 and 23.3 W/(m^2 K), separately. The temperature distribution and heat flux distribution can be illustrated by running the model in ANSYS, as shown in Fig. 2.

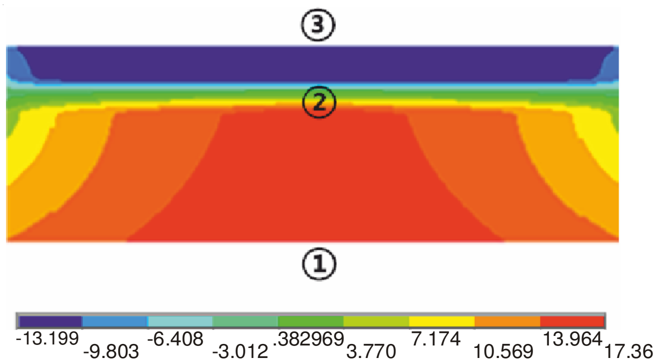

Fig. 2. Temperature distribution of ceramsite under the effect of aluminum

The results show that aluminum foil prevents the heat flows out of ceramsite effectively. As illustrated by Fig. 2, there are great changes of the temperature gradient from 12.3 °C in the internal surface of ceramsite (position ①) to 7.2 °C in the surface of aluminum foil (position ②) and then to -13.2 °C in the external surface of ceramsite (position ③). Thus aluminum foil makes the ceramsite in a high temperature field and therefore reduces the probability of internal condensation.

The reflection of aluminum foil also reduces the average heat flux intensity to 40.5 W/m^2. This implies that the thermal resistance of ceramsite is promoted by aluminum. Moreover, the results show that the thermal resistance of ceramsite under the effect of aluminum is 0.501 m^2 °C/W and the average thermal conductivity is 0.18 W/(m K), both of which meet the requirement for building insulation materials. Thus, the thermal performance of the ceramsite insulation material is significantly affected by aluminum.

To further investigate the influence of aluminum, a comparison is made between the hollow ceramsite insulation material and the material stuck on aluminum foil internally. The holistic model is again applied to measure the thermal resistance of the hollow ceramsite structure without aluminum foil and the temperature flied distribution and heat flux distribution are illustrated by Fig. 3.

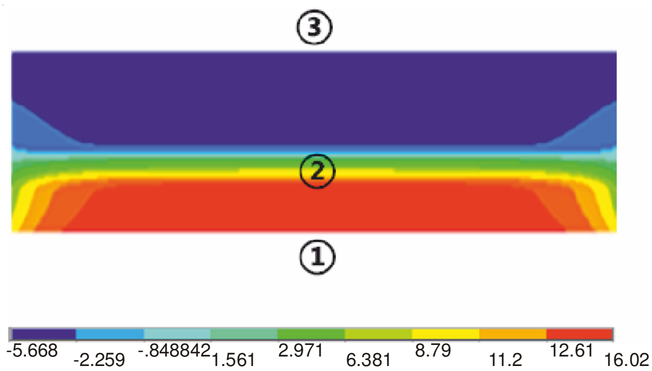

Fig. 3. Temperature distribution of ceramsite

The results indicate that the heat outflow cannot be blocked without any additional insulation material. The thermal resistance is so small that there exists a large low-temperature area (coloured blue). The area is prone to the internal condensation and further reduces the thermal resistance.

The temperature of three positions in the two conditions are shown in Table-1. The average temperature of the inner surface of ceramsite without aluminum (position ①) is 12 °C, while the temperature of position ② in is -5 °C and it further decreases to -10.5 °C in position ③. Under the effect of aluminum, the temperature of position ① and position ② is increased and the temperature of position is decreased. This is just because aluminum blocks the heat outflow.

It can be further investigated that the thermal resistance of ceramsite without aluminum is 0.250 m^2 °C/W, while the thermal resistance of ceramsite under the effect of aluminum has doubled to 0.501 m^2 °C/W. Due to the refraction of aluminum, the average heat flux intensity of the material stuck on aluminum foil internally is 40.5 W/m^2, which is a great decrease compared with the heat flux of ceramsite without aluminum (70.9 W/m^2). The average thermal conductivity of ceramsite is 0.36 W/(m K), which doesn't meet the requirement for building insulation materials. However, under the effect of aluminum, the average thermal conductivity is reduced by 50 % to 0.18 W/(m K). Table-1 shows that the thermal performance is improved by aluminum.

Application innovation: Findings in this paper have their own value of application innovation by shedding light on a better structure for architectural heat insulation, that is, the hollow ceramsite brick stuck on aluminum foil internally. To prove this, one of the most important economic indicators-the marginal thermal resistance-is taken into consideration since innovation requires not only satisfying a specific need but also being replicable at an economical cost[19]. The marginal effectiveness analysis is applied, which argues that the more added performance with the less added cost, the better[20,21].

The hollow ceramsite brick with EPS board inside is widely used in practice because of its good thermal performance. Its thermal resistance is 2.03 m^2 °C/W, which is 4.1 times higher than that of the hollow ceramsite brick stuck on aluminum foil internally (0.501 m^2 °C/W). Its average heat flux (13.5 W/m^2) is only 33 % of that of material stuck on aluminum foil internally (40.5 W/m^2). These indicate that the thermal performance of the hollow ceramsite brick with EPS board is better than the hollow ceramsite brick stuck on aluminum foil internally. However, the comprehensive cost of the hollow ceramsite brick stuck on aluminum foil internally (117 yuan/m^2 in China) is only 63.2 % of that of the hollow ceramsite brick with EPS board (185 yuan/m^2 in China).

The comprehensive cost of the hollow ceramsite brick is 105 yuan/m^2 in China and the thermal resistance is 0.25 m^2 °C/W. The marginal thermal resistance of the hollow ceramsite

TABLE-1
COMPARISON OF TEMPERATURE DISTRIBUTION AND THERMAL PERFORMANCE IN TWO CONDITIONS

Conditions	Temperature (°C)			Heat flux (W/m^2)	Thermal conductivity (W/(m k))	Thermal resistance (m^2 °C/W)
	Position 1	Position 2	Position 3			
Without aluminum	12.0	-5.0	-10.5	70.9	0.36	0.250
Under the effect of aluminum	12.3	7.2	-13.2	40.5	0.18	0.501

TABLE-2
THERMAL AND ECONOMIC FEATURES OF THE TWO STRUCTURES

Structures	Average of heat flux (W/m²)	Thermal resistance (m² ºC/W)	Comprehensive cost (yuan/m²)	Cost performance (m² ºC /W per yuan)	Combustibility
Hollow ceramsite brick with aluminum foil	40.5	0.501	117	0.021	Incombustible
Hollow ceramsite brick with EPS	13.5	2.050	185	0.022	Flammable

brick stuck on aluminum foil internally is 0.021 m² ºC/W per yuan and the cost performance of the hollow ceramsite brick with EPS board is 0.022 m² ºC/W per yuan. They are almost the same. This indicates that the hollow ceramsite with aluminum foil is almost the same economic as the hollow ceramsite with EPS. However, aluminum foil is a nonflammable material and has the potential of being used more widely. Table-2 shows the features of the two structures.

Conclusions

The effect of aluminum on the thermal performance of ceramsite is studied. By developing and applying a holistic model, the thermal resistance and thermal conductivity of ceramsite under the effect of aluminum, is measured.

• The thermal resistance of the hollow ceramsite insulation material stuck on aluminum foil internally (block with single-row core, 390 mm × 190 mm × 90 mm, 165 mm hole width, 20 mm fin thickness) is 0.501 m² ºC/W and the average thermal conductivity is 0.18 W/(m K). The average heat flux intensity of the structure is 40.5 W/m².

• The aluminum foil greatly enhances the thermal resistance of the hollow ceramsite insulation material. The thermal resistance has doubled to 0.501 m² ºC/W and the heat flux is decreased by 30.4 W/m².

• The hollow ceramsite brick stuck on aluminum foil internally is economic. Its marginal thermal resistance (0.021 m² ºC/W per yuan) is almost the same as that of material with the EPS board (0.022 m² ºC/W per yuan). The aluminum foil is incombustible, environmental friendly and widely applied and thus the hollow ceramsite brick stuck on aluminum foil internally can be a better structure for architectural heat insulation.

In conclusion, comparisons of ceramsite under the effect of aluminum and ceramsite without aluminum and ceramsite with EPS board show that aluminum greatly increases the thermal resistance and decreases thermal conductivity of ceramsite and ceramsite under the effect of aluminum has the same cost performance as that of ceramsite with EPS board. In addition, the holistic model developed in this work is also of value by providing an easy but efficient tool for measuring thermal performance. These all contribute to the literature with practical implications.

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