

# Numerical Prediction of Thermal Conductivity of Hollow Glass Microsphere-Filled Cement Composites

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**Abstract** – *Hollow glass microsphere (HGM) is a special type of inorganic spherical powder and is suitable for developing thermal-insulating composite materials. In this study, the hollow glass microsphere-filled cement composite is numerically solved for analysing its thermal transfer behavior and determining its thermal conductivity. With the help of the SEM image of the hollow glass microsphere-filled cement composite, an approximate periodic square distribution of the hollow glass microspheres in the cement matrix material is assumed so that a three-dimensional unite cell embedded with single hollow glass microsphere in the cement material phase is established for finite element analysis, from which the effect of microsphere volume fraction on the effective thermal conductivity of the composite is investigated. Results show that the thermal transfer performance of the composite remarkably decreases with the addition of the hollow glass microsphere, and will provide the reference for potential application of hollow glass microsphere-filled cement composites. Copyright © 2016 Penerbit Akademia Baru - All rights reserved.*

**Keywords:** composite, hollow glass microsphere, cement matrix, thermal conductivity, finite element

## 1.0 INTRODUCTION

The issue of thermal properties of composites is always interesting [1]. Different to conventional fiber fillers [2-5], hollow glass microsphere (HGM) is unique structure consisting of gas core and thin glass wall, and has some superior characteristics such as smaller density and lower thermal conductivity than the solid wall material [6]. Because of these characteristics, hollow glass microsphere has been applied in the fabrication of lightweight polymer-matrix or cement-matrix composites for different applications [7-12]. For example, in the context of thermal properties of HGM-filled composites, Zhu et al. investigated thermal, dielectric and compressive properties of hollow glass microsphere-filled epoxy-matrix composites by experiment and theoretical predicts [13]. Li et al. investigated the thermal insulation performance of HGM and proved that the mechanism of heat transfer in HGM is mainly of heat transfer [14]. Liang and Li measured of the thermal conductivity of hollow glass-bead-filled polypropylene composites by changing the content and size of HGM [15],

and subsequently they numerically evaluate the thermal conductivity of composites by finite element method (FEM) [16]. Patankar and Kranov investigated the thermal and mechanical properties of hollow glass microsphere filled polyethylene composites [17]. Wang et al. evaluated the effective thermal conductivity of HGM-filled cement-matrix composites by means of FEM [18]. Deepthi experimentally investigated the mechanical and thermal characteristics of high density polyethylene-fly ash cenospheres composites [19]. More recently, Ren et al. studied the mechanical and thermal properties of hollow glass microspheres/borosilicate glass composite material [20]. However, the above works rarely involved the discussion of HGM-filled cement-matrix composites, and moreover, the numerical simulation in [18] was just performed for the two-dimensional unit cell model, which is unreasonable for the case of three-dimensional microsphere particles.

Based on the findings regarding the insulation property of HGM [21-23], this study focuses on the use of hollow glass microspheres to improve the thermal insulation properties of HGM-filled cement-matrix composites. The effect of H60 HGM content (10%–40% vol) on the thermal conductivity of HGM-filled cement-matrix composites is numerically investigated by numerical methods such as finite element method for multiple material phases [24-26]. The H60 HGM is used as the raw filler material with the approximated average diameter 70 $\mu$ m to develop light-weight and thermal-insulating cement-matrix composites. The results will provide the reference for application of HGM filled cement-matrix composites, especially in building industry.

## 2.0 MICROMECHANICAL MODEL

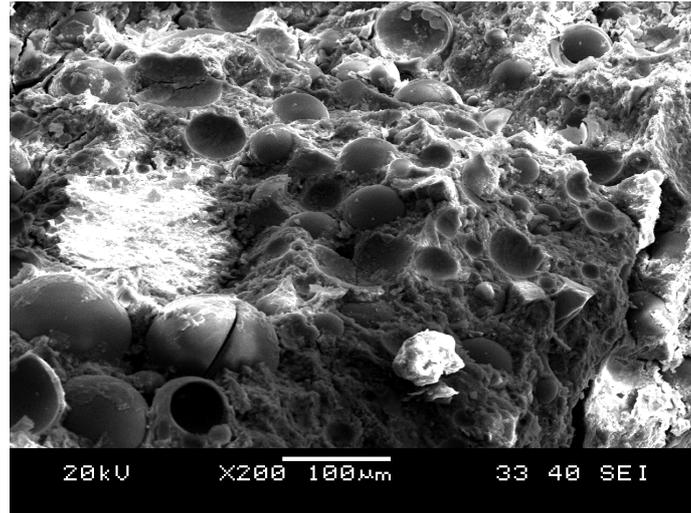
### 2.1 Physical model

Figure 1 displays a scanning electron microscope (SEM) image of cross section of the cement-matrix composite filled with 40% vol. HGMs. From Figure 1, it is seen that the hollow glass microspheres are well dispersed in the cement matrix, so it is reasonable to assume that the hollow glass microspheres distribute in the matrix in an approximate square pattern.

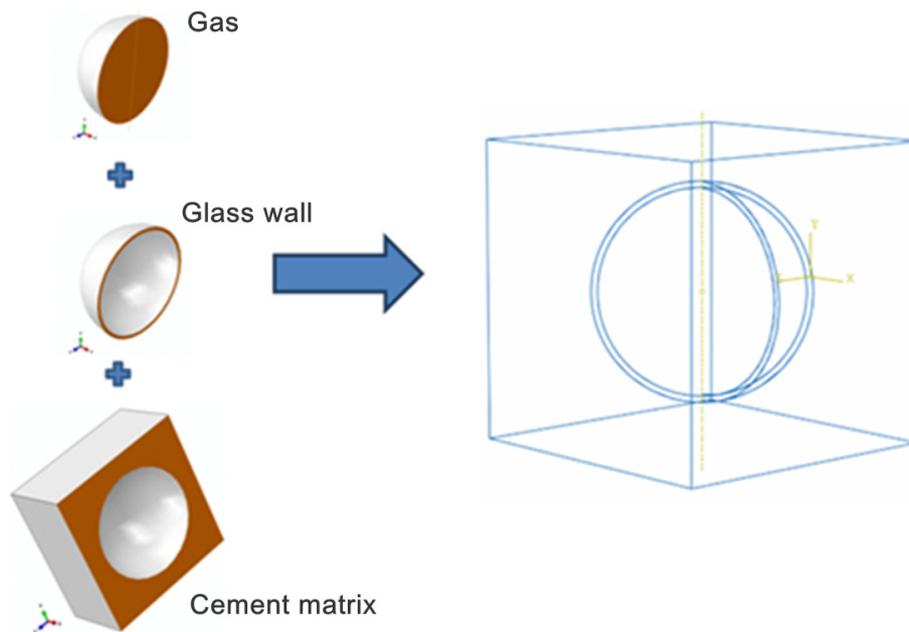
Based on this assumption, a three-dimensional representative unit cell can be taken from the composite for further analysis. Figure 2 shows the established cube unit cell model, in which three material phases including cement, wall of microsphere and inert gas are involved. Here,  $L$ ,  $R$ ,  $t$  represent the side length of unit cell, the outer radius of hollow glass microsphere and the thickness of wall, respectively. Naturally, the volume fraction of the hollow glass microsphere to the composite is defined by

$$V_s = \frac{\frac{4}{3}\pi R^3}{L^3} \quad (1)$$

In the practical analysis, it is assumed that the parameters  $R$  and  $t$  remain unchanged and the side length  $L$  can be calculated from Eq. (1) with a given value of the volume fraction  $V_s$ . Besides, the void volume fraction to the microsphere can be expressed as  $r^3/R^3$  with  $r = R - t$ .



**Figure 1:** SEM image of the section of the cement-matrix composite filled with HGMs



**Figure 2:** Physical model of the three-dimensional unit cell model consisting of three material phases

## 2.2 Physical Parameters

In this work, the used H60 hollow glass microspheres were made by Sinosteel Maanshan New Material Technology Co., Ltd in China. The microsphere's wall is made of  $\text{SiO}_2$  which has stable chemical property and smaller thermal conductivity than the cement. Moreover, the enclosing inert gas has much smaller thermal conductivity than the cement material. In Table 1, some physical parameters of H60 are listed for the finite element analysis below. Additionally, from the geometrical parameters of H60, the volume fraction of the gas void to the microsphere is about 84%, which means that most volume of the microsphere is occupied

by the gas with extremely low thermal conductivity, and thus the hollow glass microspheres are very suitable for thermal insulating materials.

**Table 1:** Basic physical properties of the composite

Particle size	Value
Average outer diameter $D=2R$ ( $\mu\text{m}$ )	70.0
Average wall thickness $t$ ( $\mu\text{m}$ )	2.0
Thermal conductivity	
Thermal conductivity of the gas $k_g$ ( $\frac{\text{W}}{\text{mK}}$ )	0.0228
Thermal conductivity of the solid wall $k_w$ ( $\frac{\text{W}}{\text{mK}}$ )	0.1793
Thermal conductivity of the cement $k_c$ ( $\frac{\text{W}}{\text{mK}}$ )	0.93

## 2.3 Effective Thermal Conductivity of Composites

### 2.3.1 Basic heat transfer equations

To evaluate the effective thermal conductivity of the composite, the heat transfer behavior in it should be fully accounted for. Similar to the heat transfer in the closed-cell foams [27], The heat transfer in the hollow glass microsphere-filled cement composite is mainly heat conduction in the cement matrix, the solid wall and the gas fluid enclosed in the microsphere, and the heat convection and radiation can be ignored, due to the facts that [16] (1) the microsphere usually has relatively small size, (2) the gas fluid is fully enclosed in the microsphere, and (3) the ratio of thermal conductivity of the solid wall phase and the gas fluid phase is extremely high. Hence, according to the three dimensional heat conduction theory in isotropic and homogeneous media, the steady-state heat conduction behaviors in the hollow glass microsphere-filled cement composite can be modeled by the following coupled energy balance equations defined respectively for the cement, solid microsphere wall and inert gas phases [28]

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

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

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

where  $T_c(x, y, z)$ ,  $T_w(x, y, z)$ ,  $T_g(x, y, z)$  represent the temperature fields in the cement matrix material, microsphere wall and gas, respectively.

According to the law of heat conduction, also known as Fourier's law, in isotropic and homogeneous media with thermal conductivity  $k$ , the heat flux vector  $q$  can be expressed in terms of temperature variable  $T$

$$\mathbf{q} = (q_x, q_y, q_z) = -k\nabla T = \left(-k \frac{\partial T}{\partial x}, -k \frac{\partial T}{\partial y}, -k \frac{\partial T}{\partial z}\right) \quad (5)$$

Thus, the heat flux vectors  $\mathbf{q}_c$ ,  $\mathbf{q}_w$ ,  $\mathbf{q}_g$  in the three material phases of the composite can be expressed as

$$\mathbf{q}_c = -k_c \nabla T_c \quad (6)$$

$$\mathbf{q}_w = -k_w \nabla T_w \quad (7)$$

$$\mathbf{q}_g = -k_g \nabla T_g \quad (8)$$

where  $k_c$ ,  $k_w$ ,  $k_g$  indicate the thermal conductivity of the cement, microsphere solid wall and enclosed gas, respectively.

For the sake of simplification, adjacent material phases, i.e. the cement and solid wall phases, and the solid wall and gas phases, are supposed to be perfectly bounded at their common interface. So the continuous conditions at the two phase interfaces can be written as

$$T_c(x, y, z) = T_w(x, y, z) \quad (9)$$

$$k_c \frac{\partial T_c(x, y, z)}{\partial n} = k_w \frac{\partial T_w(x, y, z)}{\partial n} \quad (10)$$

and

$$T_w(x, y, z) = T_g(x, y, z) \quad (11)$$

$$k_w \frac{\partial T_w(x, y, z)}{\partial n} = k_g \frac{\partial T_g(x, y, z)}{\partial n} \quad (12)$$

where  $n$  is the unit normal to the interface.

### 2.3.2 Effective thermal conductivity

In order to determine the effective thermal conductivity of the hollow glass microsphere-filled cement composite, which is assumed to be equivalently isotropic, two different constant temperature boundary conditions  $T_1$  and  $T_2$  ( $T_1 > T_2$ ) are applied on the opposite surfaces of the unit cell, i.e. the left and right surfaces perpendicular to the  $x$  –axis, to make thermal energy flow through the unit cell from left to right. The remaining four surfaces are assumed to be insulated. Figure 3 illustrates the applied boundary conditions for the unit cell.

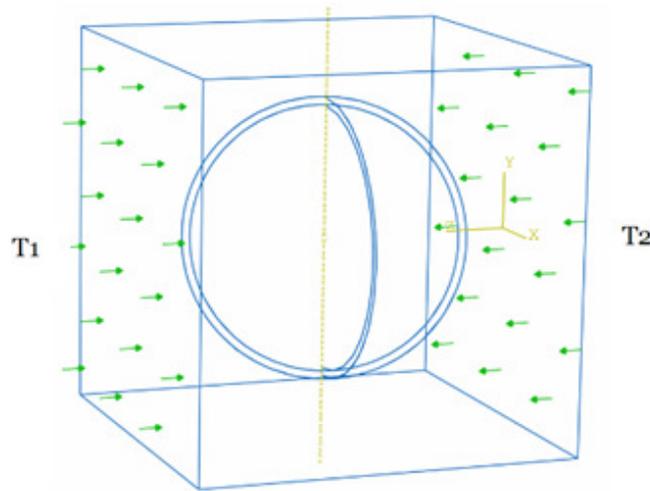
Based on the general formulation (5) of Fourier's law of heat conduction, the effective thermal conductivity of the composite can be given by [18, 3, 29]

$$k^{eff} = -\frac{\tilde{q}_x}{\partial T / \partial x} \approx \frac{\tilde{q}_x L}{T_1 - T_2} \quad (13)$$

in which  $\tilde{q}_x$  indicates the average heat flux component along the  $x$  –direction on the right surface with the constant temperature constraint  $T_2$  and can be calculate by the following integral

$$\tilde{q}_x = \int_0^L \int_0^L q_x(L, y, z) dydz \quad (14)$$

The heat transfer boundary value problem shown in Figure 3 can be solved by domain-type numerical methods, i.e. the finite element method [24] and the hybrid finite element method [30].

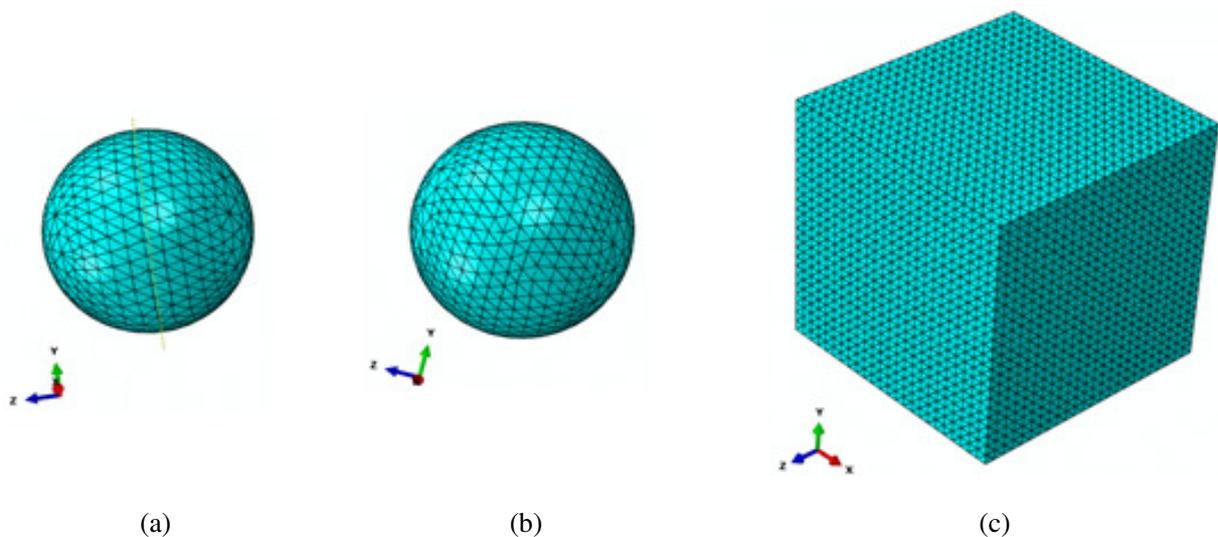


**Figure 3:** Configuration of the unit cell with specified temperature boundary conditions

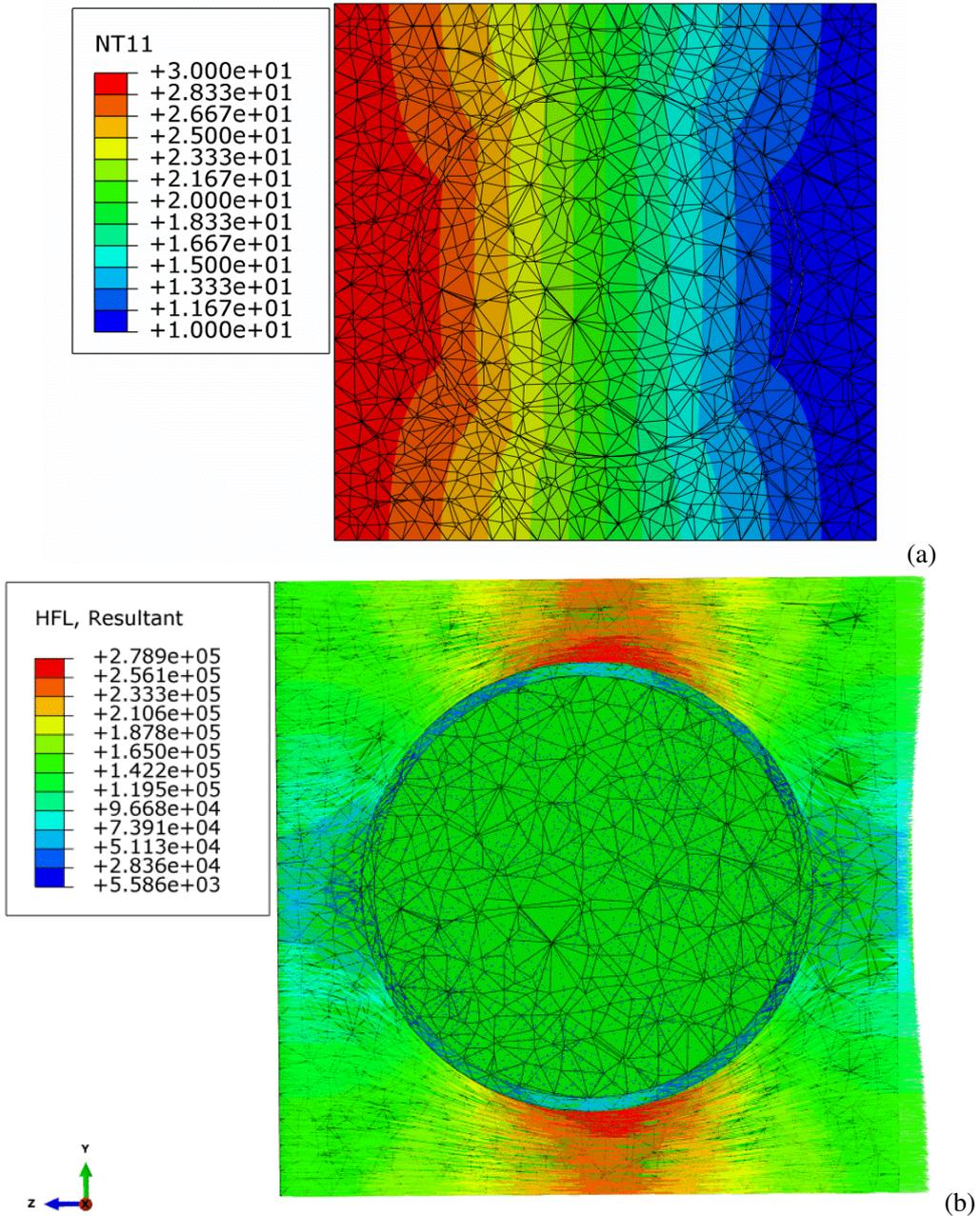
### 3.0 RESULTS AND DISCUSSIONS

#### 3.1 Heat Transfer Behavior in the Composite Unit Cell

In this section, the composite unit cell with volume fraction  $V_s = 20\%$  is taken as an example to show the heat transfer behavior in the composite cell due to the presence of hollow glass microsphere in the cement matrix material.



**Figure 4:** Mesh division for (a) gas region, (b) wall region and (c) cement matrix region

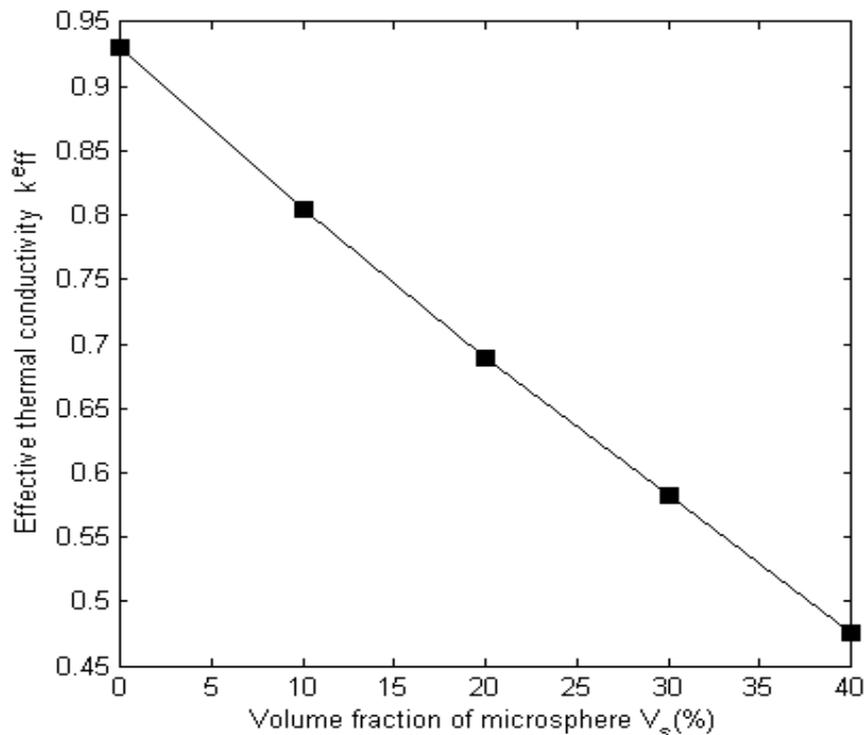


**Figure 5:** Distribution of (a) temperature and (b) heat flow in the unit cell

The constant temperature constraint  $T_1 = 30^\circ\text{C}$  and  $T_2 = 10^\circ\text{C}$  are imposed on the chosen opposite surfaces of the unit cell for numerical simulation. For the three dimensional thermal analysis in the unit cell consisting of three different material phases, 4-node linear heat transfer tetrahedron elements (DC3D4) in ABAQUS were used for discretizing the computational domain, and total 7353, 3662 and 60734 elements with 11199, 7328 and 89134 nodes are produced for the gas region, the microsphere wall region and the cement material region as displayed in Figure 4(a), (b) and (c), respectively. The variations of temperature and heat flux in the unit cell are shown in Figure 5, in which the length and direction of the arrow respectively indicate the strength and direction of the heat flow component. Fig. 5(a) reveals that the temperature distribution in the three-phase composite unit cell shows evident nonlinearity, which is caused by the presence of microsphere. Besides, it is obviously seen from Fig. 5(b) that the route of heat transfer in the composite becomes longer, owing to the hollow feature of HGM. The large difference of thermal conductivity of the wall and gas phases makes most of heat energy flow around the microsphere wall.

### 3.2 Effect of the Volume Fraction of Microsphere

In order to investigate the influence of the microsphere volume fraction on the effective thermal conductivity of the composite, we assume that the geometrical size of the microsphere including its radius and wall thickness keeps unchanged so that the side length  $L$  of the unit cell can be calculated from Eq. (1) with various values of the microsphere volume fraction ranging from 0% to 40%.



**Figure 6:** The variation of thermal conductivity to microsphere volume fraction

Figure 6 shows the variation of the effective thermal conductivity of the composite as a function of microsphere volume fractions. It is found from Figure 6 that the effective thermal conductivity of the composite significantly decreases with the increase of the microsphere volume fraction. Compared to the pure cement material with thermal conductivity 0.93 (W/mK), there are 13.5%, 25.9%, 37.3% and 48.9% decreases of  $k^{eff}$  when the microsphere volume fraction is equal to 10%, 20%, 30% and 40%, respectively. This is mainly contributed to the microsphere with lower thermal conductivity. Additionally, such decrease of the effective thermal conductivity of the composite reveals slight nonlinearity.

#### 4.0 CONCLUSIONS

The three-dimensional simulation of the cement composite filled with hollow glass microspheres is performed in this study and numerical results indicate that the hollow glass microsphere-filled cement composite has better performance of thermal insulation than that of neat cement matrix and its effective thermal conductivity dramatically decreases with the content increase of microsphere. Each increase of 10% microsphere volume fraction brings approximate 12.2% decrease of thermal conductivity of the composite, compared to the pure cement matrix. Simultaneously, the composite has lighter weight than the pure cement material with same volume, due to the addition of microsphere. Thus, the present hollow glass microsphere-filled cement composite is very suitable for developing thermal-insulating composite materials.

#### ACKNOWLEDGEMENT

The work described in this paper was partially supported by the National Natural Science Foundation of China (Grant no. 11472099) and the Creative Talents Program of Universities in Henan Province (Grant no. 13HASTIT019).

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