International Journal of Heat and Mass Transfer 81 (2015) 767–773

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental determination of effective thermal conductivity of granular material by using a cylindrical heat exchanger

Dorca Polamuri, Sunil Kumar Thamida *

Department of Chemical Engineering, National Institute of Technology, Warangal, Telangana 506004, India

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form 1 October 2014
Accepted 29 October 2014
Available online 22 November 2014

Keywords:
Granular material
Heat conduction
Effective thermal conductivity
Bruggeman's equation

ABSTRACT

Granular material in general has lower thermal conductivity than solid material. This is due to the limited contact between particles and the presence of air gaps. In the present study, a cylindrical heat exchanger is utilized to obtain temperature versus time response at the central location for a step change in wall temperature. Steel balls in spherical form are studied for estimation of effective thermal conductivity. Particle sizes studied are 12 mm, 8 mm, 4 mm, 3 mm, 2 mm and 1 mm. It is anticipated that a considerable variation in thermal conductivity would be obtained over this size range of particles. The governing equation for unsteady heat conduction in cylindrical co-ordinates incorporates the thermal diffusivity as a parameter. Hence, an analytical solution to the temperature dynamics is obtained by guessing the value of thermal diffusivity and it is used as predicted profile. The guess value of thermal diffusivity is varied and the standard deviation of error between experimental and predicted temperature profiles is minimized to find the optimum thermal diffusivity value. Later, the thermal conductivity of granular material is calculated using the definition of thermal diffusivity which involves density and specific heat capacity also. The overall temperature–time profile in dimensionless form is again compared to evaluate the deviations if any. The present results of effective thermal conductivity are also compared with prediction by Bruggeman's equation for granular material.

1. Introduction

Granular material by definition consists of small particles of a solid material of various forms such as simple spheres to ellipsoids to complicated porous clusters. We find granular material in various industrial processes in manufacture of products such as catalysts, oxides and fertilizers. More than as products the granular material finds application in raw material form for manufacture of various products in chemical industry. For instance food products in the form of powder are obtained by roasting (thermal heating of seeds) and crushing. There are other applications of heat transfer through granular material in processes such as fluidized bed drying. It is important to understand the heat transfer across a granular layer in contact with a heated metal surface like in the case of calciners [1]. The vast published literature analysis signifies the importance of heat transfer in granular media for industrial processes in applications as diversified as powder metallurgy, chemical reactors, food technology and thermal insulation [2–7].

Thermal conductivity or thermal diffusivity is an important property of any material used in designing a thermal process. Granular materials have a thermal diffusivity or conductivity much less than that of pure solids due to inclusion of air in the voids between the particles. Thermal contact resistance is another factor responsible for low thermal conductivity of granular material. For instance, if the granular material is in the form of spheres then mathematically there can be only a point contact between the neighboring granular particles. Nevertheless no natural process or manmade processes can procedure perfectly spherical granular particles and therefore there will be a finite contact area at molecular scale between the neighboring granular particles. Also packing of granular material can be random and therefore a model developed assuming symmetric packing may predict unusual results for effective thermal conductivity of granular medium [8–11].

The air present in the voids of granular material is susceptible to natural convection which in turn is found to lead to instabilities in temperature profiles due to interaction between hydrodynamics and heat transfer by thermal conduction.

In this paper, an experimental approach is presented to determine the effective thermal conductivity of granular material (steel balls) for various particle sizes. The results are compared with the

* Corresponding author.
E-mail address: sunil76@nitw.ac.in (S.K. Thamida).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.070

Nomenclature

c_p	specific heat capacity of the medium (J/kg K)
d_p	particle diameter (m)
k_{eff}	effective thermal conductivity (W/m K)
k_f	thermal conductivity of interstitial fluid (W/m K)
k_e	effective thermal conductivity of granular material (W/m K)
r, θ and z	cylindrical coordinates
r^*	dimensionless radius (= r/R)
R	radius of the inner tube (m)
s_o	volumetric heat generation (W/m^3)
t	time (s)
t^*	dimensionless time (=$\alpha\ t/R^2$)
T	temperature (°C)
T_{expt}	experimental temperature (°C)
T_{pred}	predicted temperature (°C)
T_w	wall temperature (°C)
T_o	initial temperature (°C)

Greek symbols

α_{eff}	effective thermal diffusivity (m^2/s)
ϕ_v	void fraction (dimensionless)
Θ	dimensionless temperature
ρ	density of the medium (kg/m^3)

Subscripts

e	granular material
eff	effective
f	interstitial fluid
s	pure solid

Bruggeman's correlation and found to be of similar variation with respect to particle size but quantitatively differing by a small percentage [12,13].

2. Experimental studies

2.1. Description of apparatus

Fig. 1(a) shows the schematic diagram of the experimental setup used for determining the effective thermal diffusivity of granular material samples shown in Fig. 1(b). It consists of a vertical double pipe heat exchanger. The inner tube is sealed at the bottom so that the granular material could be filled in this inner tube. The inner tube has a diameter of 50 mm and height of 300 mm. The outer tube has a diameter of 75 mm and height of 250 mm. Both inner tube and outer tube are made of stainless steel SS304 and have a thickness of 1 mm. The space between inner tube and outer tube forms an annulus. The heat exchanger is designed in such a way that the hot oil flows through the annulus.

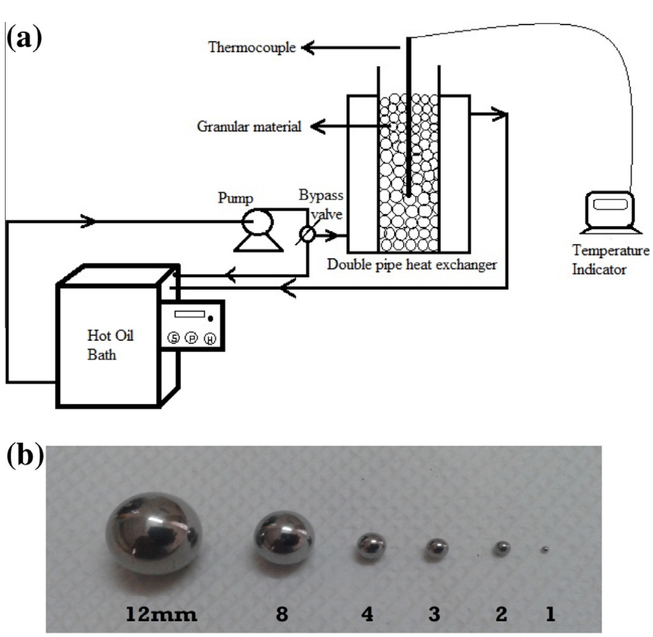

Fig. 1. (a) Schematic diagram of experimental setup and (b) steel balls used.

The hot oil is supplied from a hot oil bath where the oil temperature is maintained constant with the help of an electric heater controlled by on–off control method. The hot oil bath has a stirrer and a pump is connected to it to circulate oil continuously through the annulus of the heat exchanger. The circulation rate of hot oil is adjusted with the help of a bypass valve in order to have a minimal change of oil temperature between inlet and outlet of outer tube of heat exchanger. The reason for including a bypass valve as shown in the schematic diagram Fig. 1(a) is to avoid excess flow rates of hot oil through the shell causing leakage at clamps and pipe fittings. The temperature drop of hot oil between inlet and outlet of the shell of the heat exchanger has to be minimum possible so that the oil bath temperature could be taken as the wall temperature for the transient heat transfer process. To achieve this, a moderate hot oil flow rate is maintained. The drop in temperature of oil can be calculated as $\Delta T_{oil} = m_s\, C_{ps}\, (dT_s/dt)/m_{oil}\, C_{p\_oil}$ where m_s is the mass of granular steel, the mass flow rate of oil is m_{oil} kg/s, C_{ps} is the specific heat capacity of steel balls, C_{p_oil} is the specific heat capacity of oil and dT_s/dt is the average initial rate of increase in temperature of steel balls. It is calculated that $\Delta T_{oil} < 0.065$ °C with $m_s = 1.23$ kg, $m_{oil} = 0.022$ kg/s, $C_{ps} = 470$ J/kg °C, $C_{p\_oil} = 20{,}000$ J/kg °C and $dT_s/dt = 0.05$ °C/s being the highest rate of change in temperature of the solids from all experiments corresponding to particles sizes of 12 mm, 8 mm and 4 mm. Also the hot oil bath is equipped with an electronically controlled electric heater which maintains or brings back the temperature of the cooled and recycled oil stream to the set point temperature which is considered as wall temperature. Thus a nearly constant and uniform wall temperature is maintained for the inside tube. It is possible that the temperature of the inside stainless steel wall of the heat exchanger can be very close to the surrounding hot oil temperature because of high thermal conductivity of stainless steel. An estimate of time scale required for inner wall to reach outer wall temperature can be calculated as time $\approx \delta^2/\alpha_s$ which comes to 0.08 s with $\delta = 0.001$ m the wall thickness and $\alpha_s = 1.25 \times 10^{-5}$ m^2/s the thermal diffusivity of solid stainless steel. Since it is a small response time in comparison to the slow heating of inside granular material, the temperature of inner wall quickly reaches the outer wall temperature which is close to hot oil's temperature. An RTD sensor of PT100 type is kept inside the inner tube such that its sensor tip is located in the central portion of the inner tube. It is provided in order to measure temperature variation in the granular material that would be filled in the inner tube upto a height of 250 mm. The thermocouple is connected to a digital display where the resolution of the temperature is 0.1 °C.

2.2. Experimental procedure

Initially the stirrer of the hot oil bath was switched on to ensure uniform mixing and heating. A desired bath temperature of say 60 °C was set and the electrical heater was switched on. After the temperature reached the set point, the circulating pump was switched on. Hot oil flows through the annulus of the heat exchanger. A couple of minutes are allowed for the inner wall temperature to reach the hot oil bath temperature. Then, granular steel balls are poured into the inner tube. Immediately the temperature indicated by the thermocouple located at the center of the inner tube is noted frequently. Instead of noting down the temperature at different times, the time is noted using stop watch for every 1 °C rise in temperature of granular material. The temperature reading was noted until no further change in temperature was observed. Thus the temperature versus time data was obtained experimentally. For each particle size the experiment was repeated for three times to notice any deviation. Thus time–temperature response is obtained for a step change in wall temperature in a cylindrical vessel filled with granular material.

2.3. Temperature–time response data

The experimental data of Temperature–Time response for various particles sizes (12 mm, 8 mm and 4 mm) is plotted in Fig. 2(a). The experiments for particle sizes (3 mm, 2 mm and 1 mm) are conducted in a glass tube of diameter 15 mm and thin wall dipped in a hot water bath. Hence this experimental data is represented separately in Fig. 2 (b) since the rate of increase in temperature would be faster in a smaller diameter tube (15 mm) than in a larger diameter tube (50 mm). Since the availability of fine sized steel balls is scarce, it was chosen to conduct the experiments with smaller quantity for these three sizes in a smaller diameter tube. Nevertheless, the aspect ratio of diameter of the heat exchanger tube (glass tube) to steel balls is kept large, which is 5 for 3 mm steel balls and much higher for 2 mm and 1 mm steel balls. The initial temperature is different for different particle sizes owing to the climate change. In order compare the temperature dynamics of these different particles, a non-dimensional variable Θ is defined as $(T - T_o)/(T_w - T_o)$ where T is the temperature indicated by thermocouple measurement, T_o is the initial or room temperature and T_w is the wall temperature or the hot oil temperature. The non-dimensional temperature Θ versus time is plotted in Fig. 3(a) and (b). It can be observed that the dynamics of temperature is faster for small sized particles than for large sized particles. It implies that the effective thermal diffusivity is higher for smaller particles than for larger particles. Thermal diffusivity is mentioned here instead of thermal conductivity because in the governing equation for unsteady heat conduction, the parameter of importance is thermal diffusivity which is the ratio of thermal conductivity to the product of density and specific heat capacity. The time required to reach the steady state is less for smaller particles because the heat conduction time is proportional to R^2/α_{eff} where R is the radius of the tube, α_{eff} is effective thermal diffusivity and α_{eff} is higher for smaller size particles. Moreover, a new heat exchanger tube of diameter 15 mm (R = 7.5 mm) is used for smaller particles of size 1 mm, 2 mm and 3 mm. A mathematical model is developed in the later part of this paper that finds the optimum value of thermal diffusivity for each of the particle sizes.

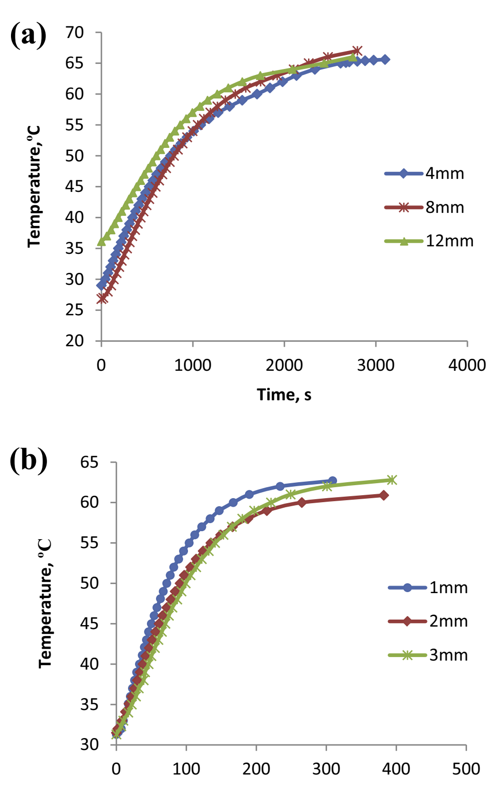

Fig. 2. Temperature variation with respect to time for various particle sizes. (a) For sizes of 12 mm, 8 mm and 4 mm. (b) For sizes of 3 mm, 2 mm and 1 mm conducted in a smaller tube.

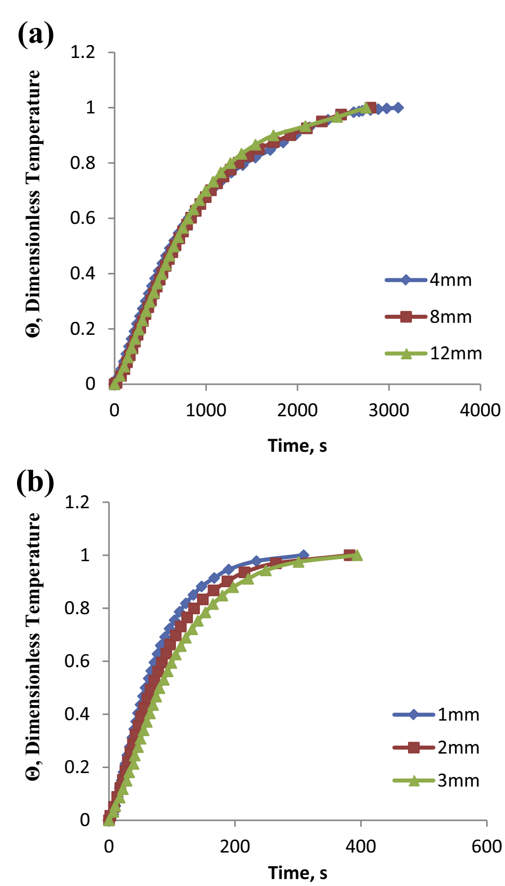

Fig. 3. Dimensionless temperature variation with respect to time for various particle sizes. (a) For sizes of 12 mm, 8 mm and 4 mm. (b) For sizes of 3 mm, 2 mm and 1 mm conducted in a smaller tube.

2.4. Determination of void fraction

Another experiment was conducted to determine the void fraction of granular steel balls of various sizes. For this purpose, a 100 ml beaker was completely filled with granular material till the 100 ml mark. After this, water was filled in the voids until it reached the 100 ml mark. The volume of water filled is noted. Now, the void fraction was calculated as the ratio of the volume of the voids or the amount of water poured to the bulk volume of the granular material, which is 100 ml. Let void fraction be ϕ_v. For smaller sized steel balls (1 mm, 2 mm and 3 mm) the void fraction is measured using 10 ml test tube.

The experimental data of void fraction versus particle size is presented in Table 1. About the void fraction of packed spherical particles, there has been quite some research [14]. As per the literature, it was found that the void fraction of packed spheres can vary from 0.26 to 0.476 depending upon the packing type for any given size of the spheres. In our experiments, the steel balls were poured into the heat exchanger tube, therefore it could be of random type packing and hence there is no particular trend of increase or decrease of void fraction with change in particle size as can be observed from Table 1.

3. Mathematical modeling

Although there are air voids, the entire volume of granular material could be considered as a homogeneous material of uniform thermal conductivity k_{eff}, density as ρ_{eff} and $c_{p,eff}$. Since the granular material is filled in a cylindrical tube, the general unsteady state heat conduction equation as in Eq. (1) for cylindrical coordinates has to be solved for the estimation of the temperature versus time at any given location [15]:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} + \frac{s_o}{k} = \frac{1}{\alpha_{eff}}\frac{\partial T}{\partial t} \quad (1)$$

where r is radial location from central axis along the tube, θ is the azimuthal angle, z is the vertical distance along the axis of the tube, s_o is the volumetric heat source inside the material, t is time, T is temperature and α_{eff} is the effective thermal diffusivity of the material. s_o the heat generation term in Eq. (1) is zero in the granular material filled inside the heat exchanger.

Since the height of the cylinder carrying granular material is large compared to diameter, the axial effect in z-direction could be neglected and azimuthally symmetry is assumed. With this assumption, the Eq. (1) reduces to Eq. (2):

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{1}{\alpha_{eff}}\frac{\partial T}{\partial t} \quad (2)$$

The boundary and initial conditions for the temperature $T(r,t)$ are as given below:

$$\text{At } r = 0,\quad \frac{\partial T}{\partial r} = 0 \text{ (symmetry condition)} \quad (3a)$$

$$\text{At } r = R,\quad T = T_w \quad (3b)$$

$$\text{At } t = 0,\quad T = T_o \text{ for } 0 < r < R \quad (3c)$$

where R is the radius of the inner tube in the cylindrical heat exchanger. Now, non-dimensional form of Eq. (3) is obtained as

$$\frac{\partial \Theta}{\partial t^*} = \frac{1}{r^*}\frac{\partial}{\partial r^*}\left(r^*\frac{\partial \Theta}{\partial r^*}\right) \quad (4)$$

$$\text{At } r^* = 0, \frac{\partial \Theta}{\partial r^*} = 0$$

$$\text{At } r^* = 1,\quad \Theta = 1$$

$$\text{At } t^* = 1,\quad \Theta = 0$$

where $\Theta(r^*,t^*) = (T(r,t) - T_o)/(T_w - T_o)$ is dimensionless temperature, $t^* = \alpha t/R^2$ is dimensionless time and $r^* = r/R$ is the dimensionless radius respectively.

4. Results and discussion

4.1. Determination of α_{eff} by optimization method

The task is that α_{eff} is the unknown. Hence a most optimum α_{eff} has to be found such that the solution to the temperature profile for $r^* = 0$ (central axis) should match with the experimentally obtained $\Theta(t)$ as shown in Fig. 3(a) and (b). Thus it is a parameter estimation problem. The approach adopted is that of optimization method. Before optimization, an analytical solution to Eq. (4) is obtained using method of separation of variables [16].

The separation of variables technique involves the representation of $\Theta(r^*,t^*) = X(r^*)\,Y(t^*)$. If this is substituted in Eq. (4), it gives Eq. (5)

$$\frac{1}{X}\frac{dX}{dt^*} = \frac{1}{Y}\frac{1}{r^*}\frac{d}{dr^*}\left(r^*\frac{dY}{dr^*}\right) \quad (5)$$

It can be noted that the partial derivatives are replaced with total derivatives. Hence the two sides of the Eq. (5) could be equal only if both are equal to a constant. It requires that the choice of this constant has to be negative in order to have $X(t^*)$ not to approach infinity for infinite time. Hence let that constant be $-\lambda^2$ so that it is always negative. Then, two ordinary differential equations arise from Eq. (5). These can be further solved by applying the boundary conditions to obtain suitable eigenvalues λ_i and eigen functions in space. A general infinite series solution by superposition principle can be represented for $\Theta(r^*,t^*)$ in terms of these eigen functions. The coefficients in the infinite series can be obtained by applying initial condition. The final solution is represented in Eq. (6):

$$\Theta(r^*,t^*) = 1 - \sum_{i=1}^{\infty}\frac{2}{\lambda_i}\frac{J_0(\lambda_i r^*)}{J_1(\lambda_i)}exp(-\lambda_i^2 t^*) \quad (6)$$

where λ_i are the roots of Bessel function of zeroth order (J_0) and J_1 are the Bessel functions of first order.

The experimental data for temperature versus time is available at the central axis of the cylindrical tube that is at $r = 0$ or $r^* = 0$.

For $r^* = 0$, the predicted temperature variation in dimensional form is

$$T(0,t) = T_w - (T_w - T_o)\sum_{i=1}^{\infty}\frac{2}{\lambda_i}\frac{1}{J_1(\lambda_i)}e^{\frac{-\lambda_i^2\alpha_{eff}t}{R^2}} \quad (7)$$

The α_{eff} value is initially guessed and optimized systemically such that the error between predicted temperature dynamics in Eq. (7) and the experimental data in Fig. 2(a) and (b) is minimized. Thus the experimental data is used for determining the effective thermal diffusivity by using MATLAB code for the analytical solution Eq. (7). Statistical method adopted to quantify the error is standard

Table 1
Void fraction for different particle sizes of steel balls.

Diameter of steel balls, mm	Void fraction, ϕ_v
1	0.39
2	0.425
3	0.4325
4	0.41
8	0.43
12	0.48

deviation between T_{expt} in Fig. 2 and T_{pred} from Eq. (7). R-square method is not applied here because it is used to quantify the fitness of a linear expression whereas the present data as shown in Fig. 2(a) and (b) is non-linear. Initial guess for α_{eff} is taken a small value and for different values of thermal diffusivity the error estimation is repeated. The standard deviation of error for different thermal diffusivity values are plotted in Fig. 4. From this figure, it could be observed that a global optimum exists for effective thermal diffusivity for each of the particle sizes. The optimum α_{eff} is obtained which shows least standard deviation as shown in Fig. 4. It is repeated for the three different experimental runs for each of the particle sizes and the average of these three values is taken as the α_{eff} for that particle size.

The estimated α_{eff} along with error bar from three different runs is plotted for each of the particle sizes in Fig. 5. It shows that α_{eff} increases with decrease in particle size. A steep increase is observed for particle size below 4 mm. There is non-monotonic variation between 4 mm and 3 mm steel balls because of change in the experimental apparatus. However, the error bars are considerable which implies that there is a band of thermal diffusivity even for mono-disperse particles which can be owed to the wide range of void fraction (0.26–0.476) possible for randomly packed spheres. Hence, this could be justifiable because the effective thermal diffusivity depends on void fraction.

In order to verify the suitability of the determined α_{eff}, a plot is obtained from the analytical expression in Eq. (7) to compare

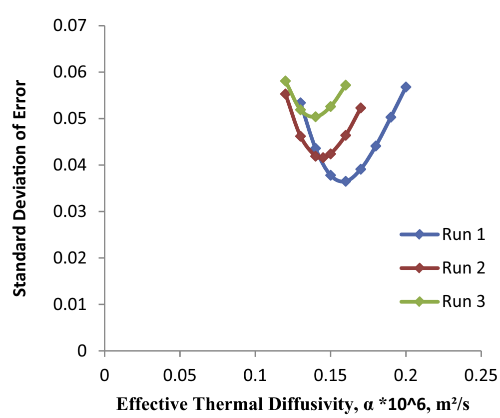

Fig. 4. Standard deviation of error between predicted and experimental Θ values for various guess values of thermal diffusivity (12 mm steel balls).

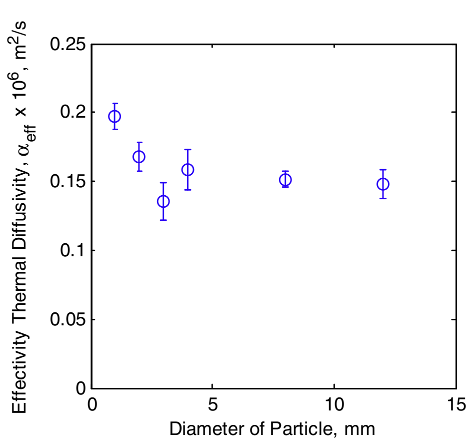

Fig. 5. Experimentally determined values along with error bar of effective thermal diffusivity of granular steel balls for various particles sizes. The experiments for sizes of 3 mm, 2 mm and 1 mm are conducted in a smaller tube.

predicted and experimental values of dimensionless temperature Θ versus time for various particle sizes of granular materials in Fig. 6(a)–(f). The deviation could be due to factors such as natural convection of air between particles. For small particles, the air gaps are also of smaller size which would minimize the natural convection. Whereas for larger particles there could be considerable heat transfer by natural convection in the voids. The hot air at the boundary of the inner tube in heat exchanger could move through the voids and reach the thermocouple tip before the temperature could rise due to conduction mode alone.

From effective thermal diffusivity, the effective thermal conductivity k_{eff} could be determined as follows:

$$k_{eff} = \alpha_{eff} * (\rho c_p)_{eff} \tag{8}$$

where $(\rho c_p)_{eff}$ could be calculated using mixture rule,

$$(\rho c_p)_{eff} = \phi_v(\rho c_p)_{fluid} + (1 - \phi_v)(\rho c_p)_{solid} \tag{9}$$

where ϕ_v is the void fraction or air volume fraction in the granular material. The fluid is air and solids are steel balls. The properties of steel and air are presented in Table 2. The obtained values of k_{eff} versus particle size are presented in Table 3.

4.2. Bruggeman's correlation method

The Bruggeman's equation has been extensively used in various areas of solid state and soft matter physics despite the availability of a rich variety of alternative, more modern homogenization theories. There are numerous examples of using the Bruggeman's equation in completely different situation for various effective transport coefficients such as electric and thermal conductivity, permittivity, permeability, diffusivity etc. For spherical particles, the classical Bruggeman's formula is used to obtain the effective thermal conductivity using following correlation:

$$\left(\frac{k_f}{k_e}\right)^{\frac{1}{3}}\left(\frac{k_s - k_e}{k_s - k_f}\right) = \phi_v \tag{10}$$

where k_f and k_s is the thermal conductivity of interstitial fluid and pure solids, k_e effective thermal conductivity of granular material, ϕ_v is the void fraction in the granular material. Rearranging the above equation as a cubic third-degree polynomial equation and using MATLAB program, it is solved and effective thermal conductivity k_{eff} was obtained for various void fractions ϕ_v. The results are tabulated in Table 3 along with experimentally determined values. Bruggeman's equation shows an error of about 2% to 13% as compared to experimentally determined values of effective thermal conductivity of granular steel balls.

The properties of steel and air are presented in Table 2. The thermal conductivity of solid steel is 46 W/m K whereas the experimentally determined effective thermal conductivity of granular steel balls is around 0.28–0.44 W/m K. It shows that the granular steel has a very low effective thermal conductivity even though the particle size is smaller. This could be due to the void fraction not changing much with decrease in particle size. And effective thermal conductive depends on void fraction because the voids are filled with air which has a very low thermal conductivity of 0.02745 W/m K. In addition, there is only a point contact between neighboring steel spheres. As shown in Fig. 1(b) the steel balls used in the present study are nearly spherical and smooth. Hence, there is scope for future studies on this aspect of effective thermal conductivity of granular material.

5. Conclusions

By neglecting the end effects in modeling the vertical heat exchanger, the axis symmetric model has predicted temperature

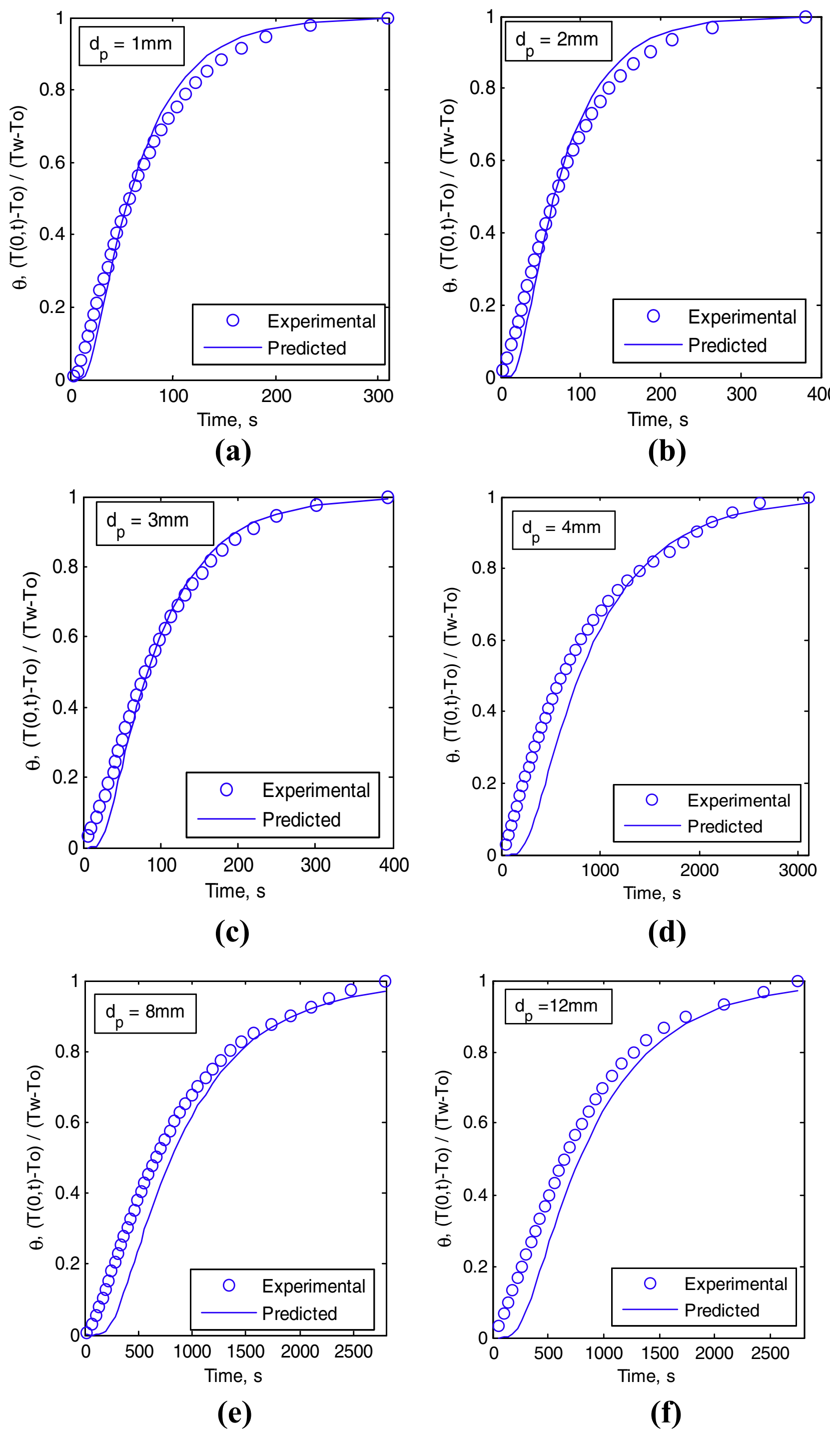

Fig. 6. Comparison of predicted and experimental values of dimensionless temperature, Θ vs time for various particle sizes of granular steel balls. (a) $d_p = 1$ mm, (b) $d_p = 2$ mm, (c) $d_p = 3$ mm, (d) $d_p = 4$ mm. (e) $d_p = 8$ mm and (f) $d_p = 12$ mm.

Table 2
Properties of steel and air.

Material	Density, ρ kg/m^3	Specific heat capacity, c_{ps} J/kg K	Thermal conductivity, k_s W/m K
Steel	7830	470	46
Air	1.1105	1006	0.02745

Table 3
Effective thermal Conductivity for different particle sizes of steel balls.

S. No.	d_p, mm	Void fraction experimental, ϕ_v	Experimental, α_{eff} * 10^6 m^2/s	Experimental, k_{eff} W/m K	Bruggeman's equation, k_{eff} W/m K
1	1	0.39	0.1969	0.4421	0.4513
2	2	0.425	0.1681	0.3558	0.3510
3	3	0.4325	0.1354	0.2828	0.3334
4	4	0.41	0.1583	0.3438	0.3900
5	8	0.43	0.1517	0.3183	0.3391
6	12	0.48	0.1483	0.2839	0.2452

versus time without much error. If the diameter of steel particle size is less than 4 mm, then there is a steep increase in effective thermal conductivity. Effective thermal conductivity obtained by Bruggeman's deviates by 2% to 13% on an average as compared to experimentally determined value. The deviation between experimental and predicted temperature versus time could be improved if the natural convection of air in the voids of granular material is also considered. Bruggeman's equation predicts effective thermal conductivity upon providing the void fraction which is a constant for perfect spheres regularly packed. Hence Bruggeman's equation gives a constant effective thermal conductivity for all sizes of steel spheres for a given packing type. Whereas, in the present work, experimental evaluation of effective thermal conductivity is carried out and it is obtained as a variable with respect to sphere sizes taking random packing effect into consideration. Hence, the present estimate of effective thermal conductivity has application in analyzing heat transfer through granular media.

References

[1] B. Chaudhuri, F.J. Muzzio, M.S. Tomassone, Experimentally validated computations of heat transfer in granular materials in rotary calciners, Powder Technol. 198 (2010) 6–15.

[2] A.M. Abyzov, A.V. Goryunov, F.M. Shakhov, Effective thermal conductivity of disperse materials. II: Effect of external load, Int. J. Heat Mass Transfer 70 (2014) 1121–1136.

[3] J.K. Carson, J.P. Sekhon, Simple determination of the thermal conductivity of the solid phase of particulate materials, Int. Commun. Heat Mass Transfer 37 (2010) 1226–1229.

[4] J. Ordonez-Miranda, J.J. Alvarado-Gil, R. Medina-Ezquivel, Generalized Bruggeman formula for the effective thermal conductivity of particulate composites with an interface layer, Int. J. Thermophys. 31 (2010) 975–986.

[5] J. Wang, J.K. Carson, M.F. North, D.J. Cleland, A new approach to modeling the effective thermal conductivity of heterogeneous materials, Int. J. Heat Mass Transfer 49 (2006) 3075–3083.

[6] D. Mandal, D. Sathiyamoorthy, M. Vinjamur, Void fraction and effective thermal conductivity of binary particulate bed, Fusion Eng. Des. 88 (2013) 216–225.

[7] M. Bahrami, M.M. Yovanovich, J.R. Culham, Effective thermal conductivity of rough spherical packed beds, Int. J. Heat Mass Transfer 49 (2006) 3691–3701.

[8] J.K. Carson, Measurement and modeling of the thermal conductivity of dispersed aluminium composites, Int. Commun. Heat Mass Transfer 38 (2011) 1024–1028.

[9] A. Abou-Sena, A. Ying, M. Abdou, Experimental measurements of the effective thermal conductivity of a lithium titanate (Li_2TiO_3) peddles- packed bed, J. Mater. Process. Technol. 181 (2007) 206–212.

[10] M.Y. Glavina, K.C. Di Scala, Roberta Ansorena, Carlos E. del Valle, Estimation of thermal diffusivity of foods using transfer functions, LWT – Food Sci. Technol. 39 (2006) 455–459.

[11] E.S. Huetter, N.I. Koemle, G. Kargl, E. Kaufmann, Determination of the effective thermal conductivity of granular materials under varying pressure conditions, J. Geophys. Res. 113 (2008) EI2004.

[12] A.V. Goncharenko, Generalizations of the Bruggeman equation and a concept of shape-distributed particle composites, Phys. Rev. E 68 (2003) 041108.

[13] D.A.G. Bruggeman, Calculation of various physical constants in heterogeneous substances. I: Dielectric constants and conductivity of composites from isotropic substances (German), Ann. Phys. 24 (1935) 636–679.

[14] F.A.L. Dullien, Porous Media: Fluid TRANSPORT and Pore Structure, second ed., Academic Press Inc., 1992.

[15] J.P. Holman, Heat Transfer, eighth ed., McGraw Hill, 1996.

[16] W.E. Boyce, R.C. Diprima, Elementary Differential Equations and Boundary Value Problems, sixth ed., John Wiley & Sons Inc., 1997.