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

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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

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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.

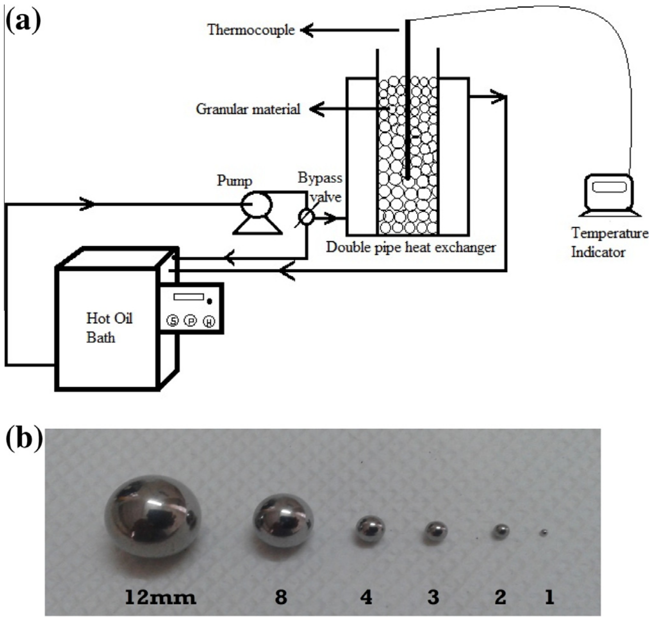

Fig. 1. (a) Schematic diagram of experimental setup and (b) steel balls used.

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.