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Estimation of volumetric heat transfer coefficient in randomly packed beds of uniform sized spheres with water as working medium

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A B S T R A C T

The advent of technology and development has led to a surge in energy demands by both developing and developed nations. Since 2000, the energy usage pattern in India has doubled. The majority of the power sector is dependent on the fossil fuel sources for energy generation. While energy generation is of prime concern the storage and retrieval with minimum losses is also significant. The packed beds system form a significant part of the solar power systems which are used to store energy during day time and retrieve it during the night. The present work investigates on the issues related to energy storage capability in packed beds.

In the present work, volumetric heat transfer coefficient is measured using a transient technique in packed beds with uniformly sized spheres. The experiments are conducted for bed to particle diameter ratios of 5, 10 and 21. The temperatures inside the packed bed are measured at four axial locations with thermocouples placed inside the spheres and positioned 112 mm apart along the central axis. The temperatures are measured at four radial locations 5, 10, 15 and 20 mm apart from the solid wall along different axial planes from the entry of packing. The experimental results are compared with Schumann's curves and the volumetric heat transfer coefficient is estimated. It is found that the estimated volumetric heat transfer coefficient (h_v) is higher for smaller particle diameter 2.38 mm as compared to larger diameter spheres with random packing. There is an increase in the volumetric heat transfer coefficient (h_v) with the increase in the particle Reynolds number.

1. Introduction

Nature has been providing alarming signals for climate change through extreme changes in weather patterns. The human activities act as catalyst in these phenomena. The increasing uses of technology gadgets and life style patterns have been influencing the energy demands of nations. A major contributor to the global warming is the sector of energy production. The recent events such as: global distribution and variation of carbon dioxide levels in air is 402.56 ppm highest since 650,000 years, global temperature has risen by 0.78 °C since 1880, the arctic ice cover has been declining at a rate of 13.4% per decade lowest on record, global sea levels are changing at a rate of 3.39 mm annually which is due to rise in temperature of oceans and melting of the glaciers, are indicators of the rate at which this phenomena is in progress [1]. The energy needs are on steep rise for all the nations and the traditional non renewable sources are a major contributor to energy generation sector. Since 2000, the energy usage pattern in India has doubled. India's primary energy consumption has increased from 60×10^3 TWh in 1970 to 130×10^3 TWh in 2012. (TWh is Trillion Watt hours of annual power consumption) [2]. Still the electricity demands to the remote areas in India are not yet met. Amongst the renewable or alternative sources of energy generation the solar power systems are contributing 2632 MW of energy under grid interactive renewable power in India [3]. While energy generation is of prime concern the storage and retrieval with minimum losses

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Nomenclature

C_{pS}	Specific heat capacity of solid, $J\ kg^{-1}K^{-1}$
C_{pF}	Specific heat capacity of fluid, $J\ kg^{-1}\ K^{-1}$
D	Bed diameter, *mm*
D_m	Mass diffusivity, m^2s^{-1}
d_p	Particle diameter, *mm*
h_v	Volumetric heat transfer coefficient, $W\ m^{-3}K^{-1}$
J_n	Bessel function of *n*th order and first kind, –
L	Length of packed bed, *mm*
L_{ch}	Characteristic length, *mm*
$\dot{m}$	Mass flow rate, $kg\ s^{-1}$
N_u	Nusselt number $= hd_p/k$, *dimensionless*
Nu_{ch}	Nusselt number based on characteristic length, *dimensionless*
Pr	Prandtl number $= \nu/\alpha$, *dimensionless*
R_h	Hydraulic radius, *mm*
Re_{ch}	Reynolds number based on characteristic length and velocity, *dimensionless*
Re_p	Reynolds number based on particle diameter, $\rho U d_p/\mu$, *dimensionless*
S_B	Particle surface area per unit volume of packed bed, m^{-1}
Sc	Schmidt number $= \nu/D_m$, *dimensionless*
t	Time, *s*
T_S	Solid temperature, °C
T_F	Fluid temperature, °C
T_{Fi}	Inlet fluid temperature, °C
U	Superficial velocity (based on bed cross-sectional area), $m\ s^{-1}$
U_F	Interstitial velocity of fluid $= (U/\varepsilon)$, $m\ s^{-1}$
V_T	Total volume of packed bed, mm^3
V_{void}	Interstitial volume of packed bed, mm^3
x	Distance of axial plane location from the bed entry, *mm*
y	Dimensionless space parameter, *dimensionless*
z	Dimensionless time parameter, *dimensionless*

Greek symbols

α	Thermal diffusivity, m^2s^{-1}
ε	Void fraction (mean), *dimensionless*
μ	Dynamic Viscosity, *Pa s*
ρ_S	Density of solid, $kg\ m^{-3}$
ρ_F	Density of fluid, $kg\ m^{-3}$

is also significant. The packed beds system form a significant part of the solar power systems which are used to store energy during day time and retrieve it during the night. The present work investigates on the issues related to energy storage capability in packed beds.

The first model for unsteady heat transfer in packed beds is developed by Schumann [4]. A mass of crushed material may be either heated or cooled by fluid passing through this porous structure formed. He formulated the laws governing the rate of heat transfer for such porous media and mathematically obtained the temperature distribution of both solid and fluid phases. The domain of interest which is considered consists of a mass of crushed material packed inside a circular pipe through which hot fluid is allowed to flow. The following are the assumptions made to obtain the governing equations:

- The packed material lumps are very small assumed to have uniform temperature at an instant of time.
- Fluid to particle heat transfer is dominating compared to heat transfer within the fluid and solid individually.
- The rate of heat transfer from solid to fluid at any position is proportional to average difference in temperature between solid and fluid at that position.
- Volume change in solid due to rise in temperature is negligible.
- The thermo-physical properties are independent of temperature rise.
- Fluid flow through the packed bed is uniform flow and incompressible in nature.

The governing equation considering the solid phase as control volume and boundary conditions are given by:

$$\frac{\partial T_s}{\partial t} = \frac{h_v}{\rho_S\, C_{pS}\,(1-\varepsilon)}(T_F - T_s) \tag{1}$$

$$At \quad x = 0(Bed\ \ entry), \quad T_S = T_{Fi}\left[1 - e^{-\left(\frac{h_v t}{\rho_S C_{pS}(1-\varepsilon)}\right)}\right]$$

$$At \quad t = 0(Bed\ \ entry), \quad T_S = 0$$

The governing equation considering the fluid phase as control volume and boundary conditions is given by:

$$\frac{\partial T_F}{\partial t} = -U_F\left(\frac{\partial T_F}{\partial x}\right) - \frac{h_v}{\rho_F C_{pF}\varepsilon}(T_F - T_s) \tag{2}$$

$$At\ \ x = 0(Bed\ \ entry), \quad T_F = T_{Fi}\ \ for\ \ all\ \ times(t \geq 0)$$
$$At\ \ t = 0(Bed\ \ entry), \quad T_S = 0$$

For a location far away from the entry of the bed ($x = U_F\, t$) the boundary condition is:

$$At\ \ x = U_F t(Deep\ \ in\ \ bed), \ \ T_F = T_{Fi}\left[1 - e^{-\left(\frac{h_v t}{\rho_F C_{pF}\varepsilon}\right)}\right]\ \ and\ \ T_S = 0$$

Using independent variables, the governing equations are transformed into a standard differential equation in Bessel form whose solution is in the form of a series.

$$\frac{T_S}{T_{F_i}} = 1 - e^{-y-z}\underbrace{\sum_{n=0}^{\infty} y^n J_n(yz)}_{SPACE\ \ PARAMETER} = e^{-y-z}\underbrace{\sum_{n=1}^{\infty} z^n J_n(yz)}_{TIME\ \ PARAMETER} \tag{3}$$

where $J_o\,(yz)$ is Bessel function of zeroth order and first kind