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Heat transfer between a packed bed and a larger immersed spherical particle

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ABSTRACT

In this paper, heat transfer coefficients between the hot packed beds of particles and the larger cold immersed sphere were experimentally determined. The packed beds consisted of mono-sized spherical glass particles of $d_p = 1.2$, 1.94 and 2.98 mm. The aluminum test spheres of $D_p = 6$, 12 and 20 mm with K-type (Ni/Al) thermocouples inserted in them were immersed into the bed. The temperatures of the test spheres were recorded until the thermal equilibrium was reached. From these recordings, heat transfer coefficients were determined. The experiments were performed in the range of gas superficial velocity of ~0.3–0.8 m/s and the bed temperature from 90 to 320 °C. It was found that the measured heat transfer coefficients increased with the increase in gas superficial velocity, while only a slight increase with temperature was observed for test spheres $D_p = 6$ and 12 mm in the investigated temperature interval. The heat transfer coefficients were generally larger for smaller test spheres, while they did not show significant dependence on the size of the bed particles.

The literature correlations for heat transfer coefficients in packed beds in form of Nusselt number and heat transfer factor j_H were compared to experimental data from this work. The correlations proposed by Collier et al. (2004) [18] and Handley and Heggs (1968) [2] fit our experimental data best. The mean error between the experimentally determined heat transfer coefficients and the ones calculated from Collier et al. (2004) [18] correlation was 12.7%.

1. Introduction

Packed beds of particles are widely used in different industries. Heat transfer processes and chemical reactions in packed beds are very common [1]. In many cases, packed beds of particles are used to enhance the heat transfer between the gaseous and solid phases. To achieve the optimal design of a packed bed, it is very important to be able to understand and predict the heat transfer behavior of the system.

In the past, several studies have been conducted in order to derive the correlations for heat and mass transfer prediction in packed beds [2–7]. The mentioned studies were focused on the overall transfer properties of the beds. Handly and Heggs [2] performed the macroscopic measurements of the overall heat transfer coefficient in beds of different packages by measuring the bulk temperature of the bed following the step change in gas temperature. Their correlation has the following form:

$$\varepsilon \cdot j_H = \frac{0.255}{Re_p^{1/3}} \tag{1}$$

Balakrishnan and Pei [3,4] critically reviewed the literature on heat transfer in packed beds and analyzed the interaction of the two major modes of heat transfer in packed beds: conduction between the particles in the bed and convection between the flowing gas and the particles.

Dwivedi and Upadhyay [5], Petrovic and Thodos [6] as well as Thoenes and Kramers [7] investigated the overall mass transfer in packed beds and derived the correlations for the prediction of mass transfer coefficient based on mass transfer factor, j_D. Their results can be applied for heat transfer coefficient prediction using the analogy of the heat and mass transfer in the packed beds $j_H = j_D$ [8].

Petrovic and Thodos [6] correlation derived from the mass transfer experiments has the following form:

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Nomenclature

A_p	particle surface
Bi	Biot number
C_{pS}	particle specific heat capacity
d_p	packed bed particle diameter
D_p	test sphere diameter
D_c	column diameter
g	gravitational acceleration
h_p	particle heat transfer coefficient
$h_{p,conv}$	convective particle heat transfer coefficient
$h_{p,cond}$	conductive particle heat transfer coefficient
H	bed height
j_H	heat transfer factor
j_D	mass transfer factor
M_p	mass of the particle
Nu_p	$= (h_p d_p)/\lambda$ bed particle Nusselt number
Nu_s	$= (h_p D_p)/\lambda$ test sphere Nusselt number
Re_p	$= (\rho_f U d_p)/\mu$ bed particle Reynolds number
Re_s	$= (\rho_f U D_p)/\mu$ test sphere Reynolds number
T_g	temperature of the gas
T_{g0}	initial temperature of the gas
T_p	temperature of the particle
U	superficial fluid velocity
U_{mF}	minimum fluidization velocity (superficial)

Greek letters

ε	voidage
λ	fluid thermal conductivity
λ_{Al}	thermal conductivity of aluminum
μ	fluid viscosity
ρ_f	fluid density
ρ_p	particle density
T	time

Subscripts

avg	average
mF	minimum fluidization
p	particle

$$\varepsilon \cdot j_H = \frac{0.357}{Re_p^{0.395}} \tag{2}$$

Dwivedi and Upadhyay [5] correlation was derived from a number of experimental results of the overall mass transfer coefficients in packed beds of different authors:

$$\varepsilon \cdot j_H = \frac{0.765}{Re_p^{0.82}} + \frac{0.365}{Re_p^{0.386}} \tag{3}$$

Bošković-Vragolović et al. [9] investigated the mass transfer from a single immersed sphere in liquid packed beds of inert particles. The correlation developed from their experiments has the following form:

$$\varepsilon^{1.2} \cdot j_H = \frac{0.395}{Re_p^{0.39}} \tag{4}$$

Ranz and Marshall [10] proposed the correlation for heat transfer from the flowing gas to the single sphere in the form of Nusselt number:

$$Nu_p = 2 + 0.6 Re_p^{1/2} \mathrm{Pr}^{1/3} \tag{5}$$

Kunii and Levenspiel [1] developed the correlation for heat transfer in packed beds in the same form with different coefficient:

$$Nu_p = 2 + 1.8 Re_p^{1/2} \mathrm{Pr}^{1/3} \tag{6}$$

More recently, the heat transfer behavior in fluidized [11–17] and packed [18,19] beds was experimentally investigated on the individual particle level. The experimental techniques were developed for following the temperature change of the object immersed in the bed. This allowed the determination of the transient heat transfer coefficients of the spherical particles [15,18,19] as well as of the objects of other geometries [20]. Collier et al. [18] developed the correlation for the prediction of the heat transfer coefficient of the sphere immersed in the packed bed, which includes the ratio of the diameters of the immersed sphere and the particles constituting the packed bed:

$$Nu_s = \frac{h_p D_p}{\lambda} = 2 + 0.90 Re_s^{0.62} \left(\frac{D_p}{d_p}\right)^{0.2} \tag{7}$$

The correlation was developed from the measurements of the temperature change of the hot sphere immersed into the cold bed of particles. The Nusselt and Reynolds numbers in their correlation were defined on the basis of the test sphere diameter, D_p.

Mathematical modeling of heat transfer in packed and fluidized beds has been conducted recently on the particle scale [20], using discrete particle simulation (DPS) coupled with computational fluid dynamics (CFD). The analysis of heat transfer mechanisms and their relative contribution has been performed. The heat transfer coefficient (HTC) for the sphere immersed in a packed bed involves three different mechanisms: convective heat transfer between the fluid and the immersed particle; conductive heat transfer between the particles in contact with the test sphere and the radiative heat transfer coefficient. The model proposed was verified by comparison with the experimental data from the literature.

Collier et al. [18] and Scott et al. [19] determined that the heat transfer coefficient (HTC) of the hot sphere immersed in the cold bed of particles increases with the increase in gas superficial velocity, until the minimal fluidization state, i.e. $U < U_{mf}$. After this point, the HTC remains relatively constant in a wide range of gas velocities. However, Zhou et al. [21] determined using the mathematical model that this is not the general relationship, but that this behavior depends on the fluid and particles properties, especially the thermal conductivities. In the case of high thermal conductivity of the particles in the packed bed, heat transfer coefficient in the packed bed can be larger than the HTC in fluidized bed when the other conditions are the same.

Zhou et al. [21] have also shown that convective heat transfer increases with gas superficial velocity, and that it is not sensitive to the particles conductivity. On the other hand, the thermal conductivity of the bed particles affects the conductive HTC considerably, especially in the fixed bed. Generally, they concluded that the convective heat transfer increased with gas superficial velocity U, while the conductive heat transfer decreased with U.

The aim of this study was the experimental investigation of the heat transfer coefficients between the packed beds of particles and the larger immersed sphere using the experimental technique described in the literature [18,19,22]. In this paper, the experiments were performed with large test spheres (D_p = 6, 12 and 20 mm) immersed in the beds of small glass particles (d_p = 1.20, 1.94 and 2.98 mm) as opposed to the experiments in the literature which were conducted using small spheres in beds of larger particles [18] or with the particles of comparable size [19]. Also, in the