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Horizontal immersed heater-to-bed heat transfer with layer inversion in gas-liquid-solid fluidized beds of binary solids

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HIGHLIGHTS

- Examine heat transfer at the layer inversion in three-phase fluidized beds.
- Heat transfer coefficient increases with increasing the polymer bead fraction.
- Superficial liquid layer inversion velocity decreases with increasing the polymer bead fraction.

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ABSTRACT

Based on the hydrodynamic characteristics at the layer inversion point in three-phase fluidized beds with binary solids, rod-to-bed heat transfer was investigated in a semi-cylindrical transparent column (0.21 m inner diameter and 1.8 m height) with polymer beads (diameter 3.3 mm, density 1280 kg/m^3) and glass beads (diameter 0.385 mm, density 2500 kg/m^3) as binary solids. Five solid volumetric ratios were investigated, with superficial liquid velocity ranging from 25.2 to 35.0 mm/s and superficial gas velocity from 0 to 12.4 mm/s. Due to the particle size effect, the heat transfer coefficient of the polymer beads was always larger than that of the glass beads for the fluid velocities tested. When the polymer bead fraction increased at the layer inversion point in three-phase fluidized beds, the heat transfer coefficient increased due to the solids holdup. For all volumetric ratios studied, increasing the superficial gas velocity led to a lower bed voidage and a higher heat transfer coefficient. When the polymer bead volumetric fraction increased in three-phase fluidized beds, the superficial liquid layer inversion velocity decreased.

1. Introduction

Three-phase fluidized beds contain liquid that possesses a higher volumetric heat capacity than the gas. As a result, heat transfer in three-phase fluidized beds is potentially attractive for applications such as ethanol fermentation using bacteria cells that require rapid heat transfer and uniform temperature. Most commercial reactors perform at a certain temperature in order to obtain high conversions; therefore, the flow characteristics and heat transfer should be favourable at that temperature. Heat can be transferred to the bulk of a reactant by either wall-to-bed heat transfer (Wasmund and Smith, 1967; Kato et al., 1981; Chiu and Ziegler, 1983; Muroyama et al., 1984, 1986), or via an immersed heat transfer surface (Baker et al., 1978; Kang et al., 1983; Kang and Kim, 1987; Magiliotou et al., 1988). The latter has the advantage that it provides heat to (or removes heat from) a specific region. For example, immersed surfaces can be utilized to reduce hot spots in fluidized bioreactors. The immersed heat transfer surfaces may either be horizontal (Lewis et al., 1982; Kato et al., 1984; Kim et al., 2003) or vertical (Lewis et al., 1982; Kang and Kim, 1987; Cho et al., 2002; Son et al., 2007).

Layer inversion can occur when bigger/less dense particles and smaller/denser particles are co-fluidized. When the liquid velocity is between the minimum fluidizing velocity and the layer inversion velocity, the smaller/denser particles report to the bottom part of the bed. On the other hand, when the liquid velocity exceeds the layer inversion velocity, the bigger/less dense particles all move to the lower part of the bed. This phenomenon is caused by the influence of the size and density of the binary particles on the drag force. The layer inversion point establishes the point where the composition of the bottom mixed layer expands to become that of the entire binary mixture. Complete mixing of the binary solids is thus achieved without the need for mechanical agitation, providing uniform and favourable conditions for heat transfer.

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Nomenclature

A_{rod}	surface area of heat transfer surface (m^2)
d_p	particle diameter (mm)
D_H	column inside diameter (mm)
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
H_B	expanded bed height (m)
H_{B0}	initial (static) bed height (m)
I	electrical current (A)
M	mass of solid particles (kg)
n	Richardson-Zaki index (–)
N	number of particle samples (–)
P	pressure (N/m^2)
Q	heat transfer rate (W)
T	temperature (°C)
ΔT_i	temperature difference between rod surface at i^{th} position and bed (°C)
$\Delta \overline{T}$	overall average temperature difference between rod and bed (°C)
U_g	superficial gas velocity (mm/s)
U_L	superficial liquid velocity (mm/s)
$U'''_{L,inv}$	superficial liquid layer inversion velocity in gas-liquid-solid fluidization (mm/s)
V	voltage (V)
X	fluid-free volume fraction of solids component (–)
Z	height of test section (m)

Greek symbols

ε	bed voidage (–)
ε_g	gas holdup (–)
ε_l	liquid holdup (–)
ε_s	solids holdup (–)
ρ_g	gas density (kg/m^3)
ρ_l	liquid density (kg/m^3)
ρ_s	solid particle density (kg/m^3)

Subscripts

1	larger, less dense component (polymer beads, PB)
2	smaller, denser component (glass beads, GB)
b	bed
h	heat transfer surface
i	angle from horizontal (see Fig. 4) (°)
inv	layer inversion point
rod	heat transfer rod

Superscripts

–	average over entire bed
″	liquid-solid two-phase system
‴	gas-liquid-solid three-phase system

Gibilaro et al. (1986) predicted variations in the layer inversion velocity as a function of the volumetric fraction of binary solids in liquid-solid fluidized beds. Chun et al. (2011) analysed the layer inversion velocity in three-phase fluidized beds with the gas-perturbed liquid model (GPLM) of Zhang et al. (1995). Rim et al. (2013) suggested a hybrid model for a volumetric polymer bead:-glass bead (PB:GB) volumetric ratio of 0.53:0.47 based on the liquid holdup correlation proposed by Han et al. (1990). Recently, Kim et al. (2017) investigated the layer inversion velocity as a function of the volume fraction of binary solids in gas-liquid-solid fluidized beds. When gas is injected at the layer inversion point in liquid-solid fluidized beds, initial bed expansion or initial bed contraction occurs depending on the volumetric fraction of the binary particles. This affects the layer inversion velocity and changes the hydrodynamic characteristics.

Kim et al. (2017) explained that initial bed expansion occurs when the lower density particles are dominant and the superficial liquid layer-inversion velocity decreases. Conversely, initial bed contraction occurs when the denser particles are dominant and the superficial liquid layer-inversion velocity increases. Also, regardless of whether initial bed expansion or contraction occurs in three-phase fluidized beds, the superficial liquid layer-inversion velocity decreases as the superficial gas velocity increases after its initial entry. Fig. 1, reproduced from the earlier Kim et al. study, shows how the bed voidage at layer inversion varies with superficial gas velocity for the same five PB:GB volume ratios as in the present investigation. The corresponding plot of gas holdup versus superficial gas velocity (but without U_g = 16.6 mm/s) appears in Fig. 2 which is calculated from the Kim et al. data.

In three-phase fluidized beds, heat transfer affects the hydrodynamics, and both are affected by the properties of the gas, liquid, and solid materials. A number of studies of immersed heater-to-bed heat transfer with single-component particles in three-phase systems have been published (Armstrong et al., 1976; Kato et al., 1984; Kang et al., 1985; Suh et al., 1985; Magiliotou et al., 1988). However, heat transfer in three-phase fluidized beds with binary

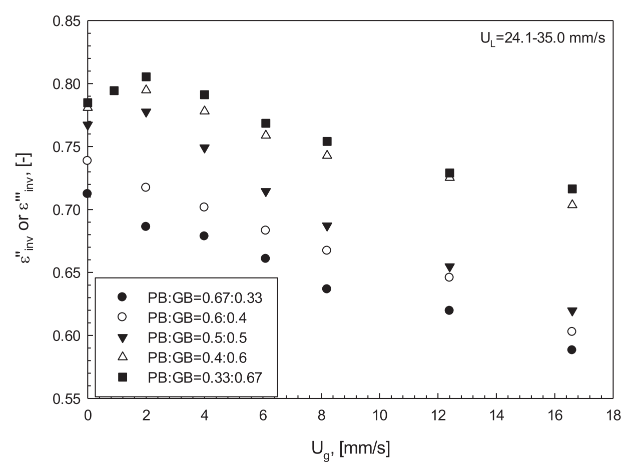

Fig. 1. Bed voidage at layer inversion as a function of superficial gas velocity for five polymer:glass bead volume ratios (Kim et al. (2017)).

solids has yet to be studied in detail. In this paper, we report on heat transfer in three-phase fluidized beds at the layer inversion point, with an immersed horizontal heat transfer tube, as a function of the solids concentration. Our investigation draws on the hydrodynamic characteristics established by Kim et al. (2017). With the binary solids volume ratio varied from PB:GB = 0.33:0.67–0.67:0.33, the superficial liquid and gas velocities were chosen to correspond to the layer inversion point.

2. Experimental

Fig. 3 shows a schematic of the experimental setup. With H_{B0}/D_H fixed at 3, the heat transfer coefficient and each phase holdup were examined in the semi-cylindrical acrylic column (inner diameter 0.21 m and height 1.8 m) as the solid volumetric ratio of polymer beads (PB) (d_p = 3.3 mm, ρ_s = 1280 kg/m^3) and