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Heat transfer and hydrodynamics in a gas-solid fluidized bed with vertical immersed internals

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ABSTRACT

An investigation of the influence of a bundle of intense vertical immersed tubes on the local heat transfer coefficients and related gas hydrodynamics of bubble frequency and gas holdup was conducted in a gas-solid fluidized bed of 0.14 m inside diameter. The heat transfer coefficient and bubble frequency and gas holdup were measured using an advanced non-invasive fast response heat transfer probe and sophisticated optical fiber probe techniques, respectively. A circular configuration of 30 vertical immersed tubes of 0.0127 m diameter occupying 25% of the cross-sectional area was employed. Glass bead solid particles with an average particle size of 210 μm and 2500 kg/m^3 solid density which representing Geldart B type was used. The experiments were performed at different superficial gas velocities, axial heights, and radial positions. It was found that the local heat transfer coefficient and local gas hydrodynamics are directly related, such that the immersed heat exchanger tubes enhanced the heat transfer by increasing the bubble frequency and local gas holdup. The current common correlations available in the literature do not predict well our results. Hence, a new correlation that account for the effect of bubble frequency and gas holdup in addition to other parameters have been developed. The effective dimensionless groups have been correlated with a good mean relative deviation value of 4.84% between the experimental and predicted values.

1. Introduction

Gas-solid fluidized beds are largely employed in numerous industrial applications, such as petroleum refining, chemicals synthesis, food and pharmaceutical production, physical operations, and power generation. For catalytic reactions, drying, coating, and combustion, due to their high heat transfer efficiency and good gas, particles mixing [1–4]. Heat transfer in these units is one of the key parameters that affect their design, scale-up, operation, and performance [5–8]. It is accomplished by the contact of the bed particles and the flowing gas with the heat exchanger surfaces, which usually they are vertical or horizontal bundle of tubes, plates, or coils. Understanding and properly quantifying the bed-to-surface heat exchange or heat transfer coefficients and the related heat transfer mechanism are required for their proper design, scale-up, operation, performance, and safety of the fluidized bed for physical and chemical operations when the control of temperature is considered as an essential need [9–11]. Three types of heat transfer mechanism between the bed and the heat exchanging surfaces exist which are particle convection, gas convection, and radiation. The overall heat transfer coefficient is the addition of the heat transfer coefficients of these types of heat transfer which his expressed as follows:

$$H_{overall} = \delta_d h_p + (1 - \delta_d) h_g + h_{rad} \tag{1.a}$$

where δ_d is a fraction of time during which any point on the heat transfer surface is occupied by particle packets, $\delta_d\ h_p$ is the particle convection component, $(1 - \delta_d) h_g$ is the gas convection component, and h_{rad} is the radiation component [12]. However, many chemical processes using fluidized beds operate at temperatures below 500 °C, where the radiation is of less significance [6,13]. These types of heat transfer mechanism are affected by the hydrodynamics of the bed.

Hence, several researchers have investigated theoretically and experimentally the behavior of heat transfer and hydrodynamics in fluidized beds as well as examined different designs and operating parameters to study the heat transfer coefficient inside different configurations of gas-solid fluidized bed vessels [14–16]. For processes with high exothermic reaction, intense heat exchanging

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Nomenclature

B_f	bubble frequency (1/s)
Cp_g	heat capacity of fluidizing gas (J/kg·K)
Cp_s	heat capacity of solid particles (J/kg·K)
D	inside column diameter (m)
d_p	particles diameter (m)
D_t	tube diameter (m)
H	axial height (m)
h	heat transfer coefficient (W/m^2·K)
k_g	thermal conductivity of the fluidizing gas (W/m·k)
Pr_g	Prandtl number of the fluidizing gas
r	radial position (m)
R	radius of the column (m)
Re_D	Reynolds number based on tube dimeter
Re_p	Reynolds number based on particle diameter
u	superficial gas velocity (m/s)
u_{mf}	minimum fluidized velocity (m/s)

Greek letters

ε	gas holdup
μ_g	gas viscosity (Pa·s)
ρ_g	gas density (kg/m^3)
ρ_s	solids density (kg/m^3)

Subscripts and superscripts

mf	minimum fluidization
p	particle

tubes are needed such as Fisher-Tropsch, Ammonia synthesis, and methanol synthesis [17–19]. Futhermore, these investigations have found that the heat transfer coefficient is affected by the following parameters [2,3,20–22]:

a. Physical properties of the solids and the gases inside the bed, including solid particles size, solids density, specific heat capacity, and the thermal conductivity, and fluid density, viscosity, and thermal conductivity.
b. Operating conditions, such as temperature, pressure, and superficial gas velocity.
c. Distributor design and heat transfer surfaces, including their geometry and location as well as the orientation of the internals relative to the fluidizing gas flow direction.

Martin [1] reported that the maximum heat transfer coefficient apparently depends on the physical properties (mainly the thermal conductivity) of the gas and the volumetric heat capacity of the solids, but this seems to be independent of the thermal conductivity of the solid. A number of experimental studies have examined the impact of the bundle of immersed tubes (internals) on the heat transfer coefficients in gas-solid fluidized beds. Borodulya et al. [23] investigated the influence of square, inline, and horizontal tube bundles with different center-to-center spacing (pitch) in a pressurized gas-solid fluidized bed with large solid particles. They found that the heat transfer coefficient is insensitive to the vibration in the horizontal and vertical pitch. Wiman and Almstedt [24] used two configuration types of horizontal tube bundles in a pressurized gas-solid fluidized bed. They concluded that the local heat transfer coefficient was higher for the tube bank configuration with a short distance between the tubes of the bundle than for those with more densely packed tubes. Kim et al. [12] studied the heat transfer and bubble characteristics in a fluidized bed with an immersed horizontal tube bundle. They found that the average heat transfer coefficient reaches its maximum value with increasing superficial gas velocity and then decreases. Lechner et al. [25] constructed a horizontal tube bundle with various tube diameters, horizontal and vertical spacing, and alignment inside a fluidized bed with solid particles of Geldart B. The reduction in the heat transfer coefficient due to the existence of the tube bank is represented by the tube bundle reduction factor, which was derived using the dimensionless geometric number of the horizontal tube bundles. The tube bundle reduction factor is a key parameter to show the reduction in the heat transfer coefficient. The results show that the reduction of the heat transfer coefficient, compared to a case using only a single tube, occurred because of the particles and gas flow disturbances caused by the immersed tubes. Recently, many studies were conducted using computational fluid dynamics (CFD) simulations to study the hydrodynamics and heat transfer in gas-solid fluidized beds with different scales, operating conditions and design parameters [26–28]. Lu et al. [27] studied the heat transfer in a gas-solid fluidized bed vessel of square shape (8 cm × 1.5 cm) without internals. The system of gas-solid is simulated with computational fluid dynamic-discrete element method (CFD-DEM) and newly proposed coarse grained particle method (CGPM). It was found that the numerical results are well compared with the experimental data for both hydrodynamics and temperature profiles and the new CGPM method can be used to simulate the heat transfer in a large scale gas-solid fluidized beds. Bellan et al. [28] examined the solid particles flow and heat transfer characteristics in a high temperature solar thermochemical fluidized bed reactor. A combined approach of computational fluid dynamic (CFD) and discrete element method (DEM) collisions model is used to develop the numerical model. Also, the discrete ordinate model has been employed to solve the radiation heat transfer that involved in this type of fluidized bed reactor. In additional to the numerical simulation, an experimental measurement system of high temperature solar thermochemical fluidized bed reactor without internals and with the same design, physical properties, and operating conditions of the numerical simulation has been presented. It was found that both numerical predictions and experimental measurements were in a good agreement. In addition, the results showed that the averaged temperature of the fluidized bed depends on the position of the top layer and focal point of the concentrated radiation and it's decreased with increasing the total mass of the fluidized bed. Lane and Ryan [26] examined the sub-grid model for the simulation of heat transfer in a gas-solid particle flow around immersed horizontal cylinder as an internal. The verification, validation, and uncertainly quantification methods have been applied to test the capabilities and limitations of the developed sub-grid model. Two modified computational fluid dynamic validation cases were implemented from the literature to compare the new simulated model. The sub-grid simulation model was applied to a conceptual pilot-scale 1 MWe carbon capture reactor to compare with substitutional modeling methods. The simulation results show fair prediction of hydrodynamics, heat transfer, and the rates of carbon capture.

Many researchers have reported the advantages of inserting vertical immersed heat exchanging tubes inside gas-solid fluidized beds for heat exchanging needs. The addition of vertical internals inside the fluidized bed can minimizes the pressure drop, slugging phenomena, bed height fluctuations, and solid particles erosion