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Heat transfer characteristics in a pressurized fluidized bed of fine particles with immersed horizontal tube bundle

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ABSTRACT

The effect of pressure on the average and local heat transfer coefficients between a submerged horizontal tube (25.4 mm-O.D.) and a fluidized bed has been determined in a fluidized-bed-heat-exchanger (FBHE; 0.20 × 0.26 × 0.58 m-high) of silica sand particles. The heat transfer coefficients were measured around the tube circumference by thermocouples. The average heat transfer coefficient (h_{avg}) exhibits a maximum value with variation of gas velocity (U_g) irrespective of pressure. The h_{avg} increases with increasing pressure at a given fluidizing number (U_g/U_{mf}) due to increase of gas density and improvement of fluidizing quality with indication of low standard deviation of solid holdup fluctuation. Variation of instantaneous local heat transfer coefficient (h_i) is a function of bubble behavior around the tube surface. The h_i exhibits higher values at the bottom than top location of the tube, and the highest value at the side of the tube (0°) at the given bed pressure. Instantanous h_i variations at the top regions (+45°, +90°) becomes much uniform with high peak frequency at higher pressures. The obtained maximum heat transfer coefficients (h_{max}) in terms of the maximum Nusselt numbers (Nu_{max}) have been correlated with Archimedes, Prandtl and Froude numbers.

1. Introduction

The pressurized circulating fluidized beds (PCFBs) have been utilized to coal combustion boilers [1], catalytic reactors such as FCC [2] and gasifier [3]. The PCFBs have adopted fluidized bed heat exchangers (FBHEs) with heat transfer tubes immersed in the bed to remove heat of combustion or heat generated by the reaction, because heat transfer between immersed tubes and the fluidized bed is extremely high due to vigorous contact of solid particles with the surface [4,5].

The heat transfer to immersed tubes from a fluidized bed has been extensively investigated over the last few decades [6]. Most of the fluidized bed heat transfer data were obtained at atmospheric pressure [7,8], and the results in pressurized gas fluidized beds with horizontal tubes are relatively sparse in the literauture. The studies in pressurized system have reported that the change in pressure predominantly affects the gas convective component due to the variation of density of the interstitial gas in the dense phase. It was further suggested that the heat transfer coeefficient is greater under higher pressre, and the influence of pressure on heat transfer coefficient diminishes with the reduction of particle size [9,10]. The predominant contribution to heat tranfer coefficient for fine particles comes from particle convection and this is not significantly affected by pressure [11]. However, it is also suggested that the increase in pressure improves the fluidization quality and hence may give rise to an increase in the heat transfer coefficient [12]. From the above previous studies, it is common that heat transfer coefficient generally increases with increase in pressure irrespective of particle size. However, most studies have been carried out in fluidized beds of coarse particles over 500 μm. Experimetal studies in pressurized fluidized bed of fine particles with horizontal tube are required for FBHE applications in PCFB, because bed materials in FBHE of PCFB are re-circulating particles, which are fines less than 500 μm [1,3] and have different solids behaviors in the bed. Most of the existing heat transfer models have maximum heat transfer coefficient (h_{max}) as a common parameter [7]. Although many empirical correlations have been reported, reliable prediction of the h_{max} considering the pressure effect is required for designing FBHE of the fine particles in PCFB [6].

In this study, the effects of gas velocity and system pressure on the average and local heat transfer coefficients between a submerged horizontal tube and the fluidized bed have been determined in a FBHE of fine sand particles. To predict maximum heat transfer coefficient between the immersed tube and fine particles bed, a correlation is proposed with the experimental data in the present and previous studies regarding on the pressure effect.

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Nomenclature

a constant
A_{tube} surface area of tube (m^2)
Al laminar flow Archimedes number, $\sqrt{d_p^3\rho_g}(\rho_p-\rho_g)g\mu_g^{-1}$(-)
Ar Archimedes number, $d_p^3\rho_g(\rho_p-\rho_g)g/\mu_g^{-1}$(-)
C_c heat capacity of cluster (J/kg K)
C_{pg} heat capacity of gas (J/kg K)
C_{ps} heat capacity of solid particles (J/kg K)
d_p mean diameter of particle (m)
Fr_p Froude number based on particle diameter, U_{mf}^2/d_pg (-)
g acceleration due to gravity (m s^{-2})
h heat transfer coefficient (W/m^2 K)
h_{avg} average heat transfer coefficient (W/m^2 K)
h_g gas convective heat transfer coefficient (W/m^2 K)
h_i local heat transfer coefficient (W/m^2 K)
h_{max} maximum heat transfer coefficient (W/m^2 K)
I electric current (A)
k_c thermal conductivity of cluster (W/mK)
k_g gas conductivity (W/mK)
Nu Nusselt number, hd_p/k_g (-)
Nu_g gas convective Nusselt number in tube top section, h_gd_p/k_g (-)
Nu_{max} maximum Nusselt number based on particle diameter, $h_{max}d_p/k_g$ (-)
Nu_p Nusselt number based on particle diameter, hd_p/k_g (-)
Pr Prandtl number, $C_{pg}\mu_g/k_g$ (-)
Q heat transfer rate (W/m^2)
T_b bed temperature (K)
T_s temperature of tube surface (K)
t penetration time of the applied heat flux to the other side of the cluster (s)
U_g gas velocity (m/s)
U_{mf} minimum fluidization velocity (m/s)
V electric voltage (V)

Greek Symbols
δ gas gap thickness (m)
$\bar{\delta}_1$ absolute average percentage deviation (-)
$\bar{\delta}_2$ root-mean-square percentage deviation (-)
ΔP pressure drop (Pa)
Δz height difference (m)
ε_s cross-sectional average solid holdup (-)
μ_g gas viscosity (Pa-s)
ρ_c cluster density (kg/m^3)
ρ_g gas density (kg/m^3)
ρ_p apparent density of solid particle (kg/m^3)

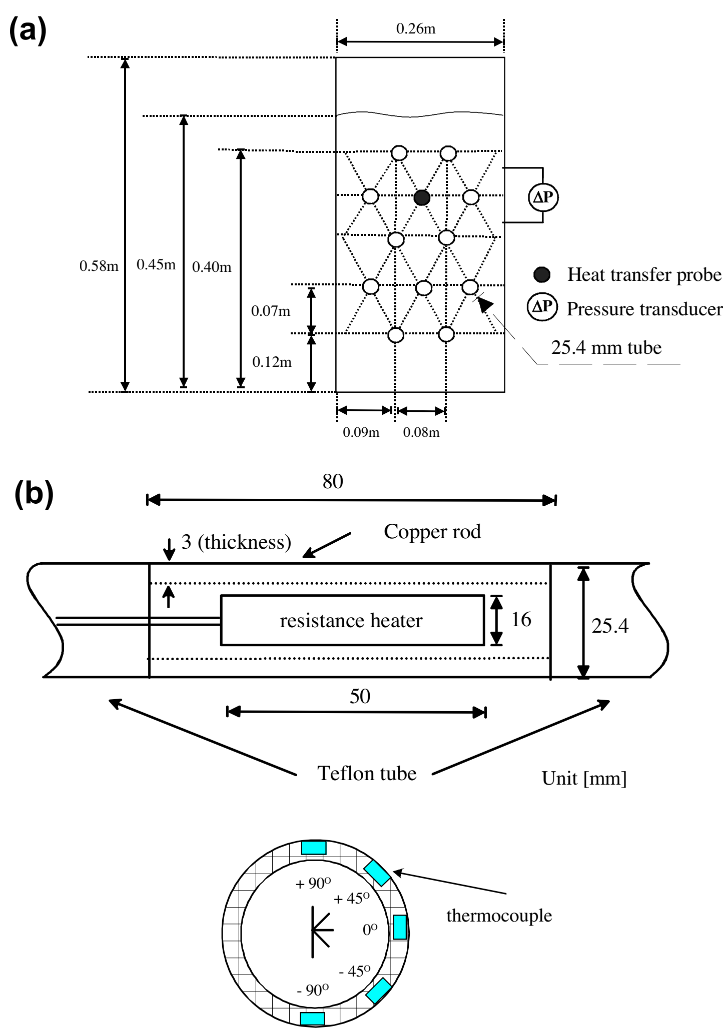

Fig. 1. Schematic diagram of (a) FBHE and (b) heat transfer probe.