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Simulation of countercurrent gas–solid heat exchanger: Effect of solid loading ratio and particle size

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Abstract

Simulation of countercurrent gas–solid heat exchanger using one-dimensional, two-fluid model has been carried out and predictions compared with experimental data reported in literature and found satisfactory. Effect of solid loading ratio, particle size and their interactions on heat transfer rate, temperature profile and thermal effectiveness of gas have been studied. Heat transfer rate was found to increase with increasing solid loading ratio and decreasing particle size. Higher heat recovery can be achieved for large particles at high solid loading ratios, while it can be achieved with wide range of solid loading ratios for small particles. Scope for further study is highlighted.

Keywords: Countercurrent; Gas–solid heat transfer; Solid loading ratio; Particle size

1. Introduction

Operations and reactions involving solids and gas are common in chemical, mineral, cement, pharmaceutical and power industries. The movement of gas and solid can either be in co-current, cross current or countercurrent mode. Gas–solid heat transfer finds wide applications in preheating, cooling, drying, pyrolysis and combustion. Experimental and simulation studies on co-current drying have been widely reported [1–5], in which the driving force has been found to decrease with height, resulting in wide variation of heat and mass transfer rate with height. This can be circumvented through countercurrent contact of gas and solid, wherein solids particles fall down through a column of upward flowing gas at a velocity lesser than the terminal velocity of the particles. This is similar to conventional countercurrent heat exchanger, resulting in more uniform heat transfer and higher heat recovery. Residence time of solids in the column can be tuned by altering the gas flow rate. Countercurrent gas–solid heat exchanger finds application for heat recovery in power industries. Decher [6] proposed the concept of falling particle heating exchanger, in which hot particles were dropped into upward flowing cooling air for power plant applications. Thayer and Sekins [7] carried out experimental and numerical studies using particles with phase change (melting) to maintain higher local temperature gradient between gas and particles. Numerical analysis of countercurrent gas–solid heat transfer system for regeneration was carried out by Gat [8] and Park et al. [9].

Experimental studies on countercurrent gas–solid heat exchanger system have been carried out by Islam [10], Sagoo [11] and High [12]. Frain [13] carried out experiments using solid distributor for better distribution of solids in to the column and found that heat recovery was enhanced by the use of distributor. Simulation using a two-dimensional model was also performed. Heat transfer

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Nomenclature

A	cross sectional area of the duct (m^2)
A_g, A_s	cross sectional area occupied by gas phase and solid phase, respectively
C_d	drag coefficient (–)
C_p, C_{ps}	specific heat of gas and solid, respectively (J/kg K)
D, D_p	diameter of duct and particle, respectively (m)
F_{fg}	frictional force per unit length between gas and the wall (N/m)
F	fluid–solid interaction forces per unit length (N/m)
h_c	convective heat transfer coefficient (W/m^2 K)
h_p	gas-particle heat transfer coefficient (W/m^2 K)
M	mass flow rate (kg/s)
N_s	number of particles per unit volume (m^{-3})
Nu_p	gas-particle Nusselt Number (–)
P	pressure (Pa)
Pr	Prandtl number (–)
Q_g	heat transfer rate from gas to solids, per unit length (W/m)
Q_l	rate of heat loss from gas, per unit length (W/m)
Q_s	rate of heat gain by solid from gas, per unit length (W/m)
Re	Reynolds number (–)
Re_p	particle Reynolds number (–)
T	temperature (°C)
U	velocity (m/s)
W	work per unit length between the phases (N)
X	distance in axial direction (m)

Greek symbols

μ	viscosity of gas phase (kg/ms)
ρ	density (kg/m^3)

Subscripts

g	gas phase
p	particle
S	solid phase

in countercurrent heat exchanger without solid distributor was also investigated by Frain [13] for solid loading ratios (solid to gas mass flow ratio) from 0.88 to 7.24. Reports on effect of particle diameter, solid loading ratio and their interactions on performance of countercurrent gas–solid heat exchanger are rarely available in the literature and a numerical study of the same using one-dimensional, two-fluid model is attempted here.

2. Model

A one-dimensional, two-fluid model is formulated with following assumptions.

(i) Gas phase is ideal, particle–particle interactions are neglected.
(ii) Pressure gradient in the solid phase momentum balance equation is neglected.
(iii) Only heat and momentum interaction between the phases are considered, with the force of interaction between the phases being drag only.
(iv) Heat transfer between wall and particles, electrical forces, surface tension forces, Saffman lift forces, Magnus forces and capillary forces are neglected

Accordingly the governing equations for the gas and solid phases are as follows:

Gas phase momentum balance equation:

$$\frac{d(m_g u_g)}{dx} + A\frac{dP}{dx} = -F_{fg} + F_g + A_g \rho_g g \tag{1}$$

Gas phase energy balance equation:

$$\frac{d(m_g C_p T_g + 0.5 m_g u_g^2)}{dx} = Q_g - Q_l - W - m_g g \tag{2}$$

Solid phase momentum balance equation:

$$\frac{d(m_s u_s)}{dx} = -F_s + A_s \rho_s g \tag{3}$$

Solid phase energy balance equation:

$$\frac{d(m_s C_{ps} T_s + 0.5 m_s u_s^2)}{dx} = Q_s - W + m_s g \tag{4}$$

Gas-wall friction has been modeled using Blasius equation. Particle Reynolds number (Re_p) is given as

$$Re_p = \frac{\rho_g |(u_g - u_s)| D_p}{\mu_g} \tag{5}$$

Drag force is given by

$$F_s = -F_g = \frac{3 C_d A_s \rho_g A^{0.65} (u_g - u_s)|u_g - u_s|}{4 D_p A_g^{0.65}} \tag{6}$$

Eq. (6) incorporates gas–solid drag coefficient C_d and the expression for drag force which are modified to take into account of multi-particle effects [14]. Drag coefficient was estimated using the empirical correlations given in literature [14].

The cross sectional areas occupied by the gas and solid phases are A_g and A_s, respectively and are related to velocity and density of the respective phases by continuity equations as follows: