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Heat transfer and phase change in a polystyrene packed bed during melting

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ABSTRACT

Phase change and heat transfer in a polystyrene packed bed during melting were experimentally and numerically investigated. When the polystyrene particles were melted, the calculated porosity decreased at the bottom and side walls and increased at the top wall. The tendency of the calculation agreed qualitatively with the observation of the visualized packed bed. However, the interfacial position between the gas layer and the packed bed near the central axis could not be reproduced by the calculation. This may be accounted for by the following two reasons. Firstly, it is not considered in the calculation that the particles above the interfacial position between the gas layer and the packed bed tend to move over the interfacial level due to the buoyancy of the gas in the not-melted packed bed. Secondly, in the experiments, some of the exhausted gas at the melting positions may move not only upward but also to the central region in the packed bed. For the heating rate of a drying oven at $\dot{T}_d = 50$ K/h, the measured temperatures at all six positions increased linearly over time and agreed well with the calculated temperatures for all positions. On the other hand, the measured temperatures could not be reproduced by the calculated temperatures except for at the points near the bottom wall at $\dot{T}_d = 500$ K/h. Numerical simulation of heat transfer with natural convection in the packed bed before melting was conducted. As the natural convection strongly influenced the heat transfer in the packed bed, the calculated temperature in the packed bed did not agree with the experimental temperature before melting at $\dot{T}_d = 500$ K/h.

1. Introduction

Modeling two-phase flow in a packed bed with melting of solid particles is an important subject for material processing and heat transfer operations in various industries. A quintessential example is the fluidized bed reactor. Not only do the particles and fluid exchange momentum across moving interfaces, but the chemical reactions also introduce heat and mass transfer into the problem and erode the solid surface. The coupling among various processes imparts a complexity to the system far beyond that of inert multiphase flow.

Either of two simulation models can be used to calculate the multiphase flow. One is a Lagrange–Euler model. In this model, the solid phase is represented by solid particles that obey Newton's law of motion, written in Lagrange space. The gas or liquid phase is treated using a Eulerian model represented by Navier–Stokes equations. Gan et al. [1] conducted a numerical simulation on melting solid particles using an arbitrary Lagrangian–Eulerian (ALE) scheme. Their simulation code [1] was validated and agreed well with the analytical solution during freezing on a cylinder without flow by Carslaw and Jaeger [2]. Their results [1] showed that a pair of particles separated at low Grashof number and attracted each other at high Grashof number. Dierich et al. [3] conducted a numerical simulation for melting many particles using the ALE scheme. Their simulation code [3] was also validated and agreed well with the analytical solution of Carslaw and Jaeger [2]. The number of particles was from 1 to 32. Their results [3] showed that the multiple ice particles with rotational effect melted faster than those without the effect during rising in an enclosed cavity.

On the other hand, in most previous reports on the melting process, the Euler–Euler model has been used to calculate heat and mass transfer. This model uses volume averaged mass, momentum and energy conservation equations written for each phase in Eulerian space. Wang et al. [4] conducted a numerical simulation based on the kinetic theory of granular flow [5] without melting. Their simulation results for heavy particles – light liquid flow in a horizontal pipe [4] agreed well with the experimental results for not only particle velocity distribution and particle volume fraction distribution but also the relationship between pressure drop and

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Nomenclature

a_{PS}	surface area of the polystyrene particle per unit volume in the packed bed [m^2/m^3-packed bed]
C_{PS}	heat capacity of polystyrene [J/(kg K)]
$C_{P,G}$	heat capacity of gas [J/(kg K)]
D_B	bubble size in melting polystyrene (=0.0015 m) [m]
D_{PS}	particle size of polystyrene (=0.0034 m) [m]
D_H	hydraulic diameter [m]
h_{PS}	heat transfer coefficient between polystyrene and gas [W/(m^2 K)]
H	top of the packed bed (=0.098 m) [m]
Δh_m	melting enthalpy of polystyrene as defined by Eq. (3) [J/kg]
I	grid number along radial position in the packed bed [–]
I_{max}	maximum grid number along radial position in the packed bed [–]
J	grid number along axial position in the packed bed [–]
J_{max}	maximum grid number along axial position in the packed bed [–]
r	radial position in the packed bed [m]
$r_{cal}(I)$	calculated radial position at the grid number I in the packed bed [m]
p	fluid pressure in the packed bed [Pa]
R	radius of packed bed (=0.0285 m)[m]
R_G	gas constant(= 8.314 J/(mol K)) [J/(mol K)]
T_0	initial temperature [K]
Td	heating rate of a drying oven [k/h]
T_M	melting point of polystyrene (=453 K) [K]
T_G	temperature in the gas phase [K]
T_{PS}	temperature of polystyrene [K]
$T_{PS,cal}(I, J)$	calculated temperature of polystyrene at $r = r_{cal}(I)$ and $z = z_{cal}(J)$ [K]
t	operation time [s]
u_G	r-component air velocity in the packed bed [m/s]
v_G	z-component air velocity in the packed bed [m/s]
$V_G(I, J)$	volume of exhausted gas at $r = r_{cal}(I)$ and $z = z_{cal}(J)$ [m^3]
$V_{G,tot}(I)$	total volume of exhausted gas at $r = r_{cal}(I)$ [m^3]
$\overline{V_\infty}$	average equilibrium volume of the packed bed [m^3]
W_{PS}	initial weight of polystyrene in the packed bed [kg]
z	axial position in the packed bed [m]
$z_{cal}(J)$	calculated axial position at the grid number J in the packed bed [m]

Greek symbol

ε	porosity [–]
$\varepsilon_{cal}(I,J)$	Calculated porosity at $r = r_{cal}(I)$ and $z = z_{cal}(J)$ [–]
ε_0	initial porosity (=0.410) [–]
ε_∞	average equilibrium porosity of packed bed (=0.185) [–]
λ_{PS}	thermal conductivity of polystyrene [W/(m K)]
λ_G	thermal conductivity of gas [W/(m K)]
μ_G	viscosity of gas [Pa s]
ρ_{PS}	density of polystyrene (=1050 kg/m^3) [kg/m^3]
ρ_G	density of gas [kg/m^3]
τ_{rr}	components of the stress tensor for Newtonian fluids in cylindrical coordinate in Eq. (8) [N/m^2]
τ_{rz}	components of the stress tensor for Newtonian fluids in cylindrical coordinate in Eq. (9) [N/m^2]
τ_{zz}	components of the stress tensor for Newtonian fluids in cylindrical coordinate in Eq. (10) [N/m^2]

mean velocity. Furthermore, they [4] discussed for light particles – heavy liquid flow in not only a straight pipe but also an elbow one. Hao et al. investigated the melting of a granular packed bed in horizontal forced convection experimentally [6] and numerically [7]. Not only the governing equations but also the discretization scheme were reported in detail for the liquid–solid two-phase flow in their paper [7]. Their calculated results [7] agreed well with the experimental results [6] in the time course of not only the mass change of the packed bed but also the bed thickness from the bottom. Xu et al. [8] investigated the thermal performance of a packed-bed molten salt thermocline thermal storage system using numerical simulation. They [8] collected previous effective thermal conductivities and previous heat transfer coefficients, which were important for conducting the numerical simulation for heat transfer and fluid flow in a packed bed. Their calculated results [8] agreed well with the experimental results [9] in the time course of the temperature profile in the packed bed. They [8] concluded that the interstitial heat transfer coefficient and the effective thermal conductivity taken from the literature lead to a negligible difference in the predicted thermal performance.

According to the above results [1,3,4,6,8], heat and mass transfer in liquid–solid two-phase flow when the temperature was less than 373 K (below the melting point) could be almost reproduced by the numerical simulation. When the temperature was higher than the melting point, it is necessary to investigate in taking into account for not only the melting enthalpy but also porosity change in the packed bed. However, high temperature processes (373 K) in gas–liquid–solid three-phase flow, for example, plastic melting, have not been investigated in detail.

In this study, phase change and heat transfer in the polystyrene packed bed during melting were investigated experimentally and numerically. Furthermore, numerical simulation for natural convection in the packed bed below melting point was conducted and discussed.

2. Experimental apparatus

Fig. 1 shows the experimental setup for visualization and temperature measurement in a melting packed bed of plastic particles. In order to heat the packed bed, a drying oven having a maximum output of 1.4 kW was used. Polystyrene rods, which were made by Kishida Chemical Co. Ltd., were used as the plastic particles. The density of the polystyrene rods was described in the Kishida Chemical Co. Ltd‘s safety data sheet in Japanese. The value of the density was 1050 kg/m^3. As both their diameter and their length were about 3 mm, the equivalent diameter of them was about 3.4 mm. Before the experiments, the polystyrene particles were put into a Pyrex glass beaker of about 57 mm in internal diameter and 98 mm in height. After the Pyrex beaker was placed in the oven, an experiment was started with a designated heating rate up to about 523 K. The experiments were conducted twice for each heating rate. One run of the experiment was for visualization using a digital video camera. The other run of the experiment was for temperature measurement in the packed bed. Fig. 2 shows the installed positions of thermocouples. The temperatures were recorded on a hard disc of a computer through a data-logger. The experimental conditions are listed in Table 1.

3. Numerical simulation

3.1. Unsteady thermal conduction in the packed bed

Two-dimensional numerical simulation in the packed bed of the polystyrene particles for heat transfer was conducted. The size of