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Solidification and melting behaviors and characteristics of molten salt in cold filling pipe

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ABSTRACT

The solidification and melting phenomena and performances of molten salt during cold filling process in a straight pipe are numerically investigated using volume of fluid model. As the molten salt is filled into a cold pipe, the molten salt adjacent to the cold wall is rapidly cooled, and the solidification phenomena appears. After the whole pipe is filled, the solidification layer begins to melt by high temperature fluid heating. Because of the solidification layer, the flow section obviously shrinks, and the pressure loss remarkably increases. During the solidification and melting processes, the fluid temperature in the region with phase change only varies near the freezing point, and it quickly rises after the melting process. Because of the absorption or release of latent heat, the boundary heat flux of molten salt is increased in the solidification region, while it will be decreased in the melting region. As the inlet temperature rises, the pressure loss apparently decreases with the thickness of solidification layer decreasing. However, when the inlet flow velocity increases, the thickness of solidification layer decreases, but the flow resistance without phase change increases, so the pressure loss has a maximum at moderate flow velocity.

1. Introduction

The molten salts have recently been used as a suitable medium for heat removal and storage at high temperature in solar energy system [1], aerospace science and technology [2], and so on. As heat storage and transfer fluid, molten salts have many advantages as large thermal capacity, low viscosity, low vapor pressure, and a wide range of operating temperature [3]. On the other hand, the freezing points of molten inorganic salts are normally not high enough [4], so the solidification phenomena of molten salt can be a serious problem for the pipe jam and material breakage.

The filling process is an important problem in the startup stage of molten salt system, and it generates many scientific topics of fluid dynamics, heat transfer, and phase change. Bergan [5] first tested the external molten salt solar central receiver as part of the Molten Salt Electric Experiment, and found that the receiver was filled at temperatures below the freezing point of salt when the salt was hot. Pacheco et al. [6] demonstated the cold fill experiments by flowing molten salt through cold panels, and then measured the transient thermal responses and penetration distance. Moreover, Pacheco and Dunkin [7] further investigated the freeze-up and recovery events of a molten salt receiver, and considered the phase change effects of molten salt.

Since the filling process of molten salt is an unsteady multiphase flow, it is difficult to obtain the local dynamical and thermal parameters, and the numerical method can benefit these investigations. Various numerical methods including VOF (Volume of fluid) [8], and phase field method [9] have been used to simulate the multiphase process. Geng et al. [10] proposed three-dimensional finite element method to investigate the filling simulation of injection molding. Shin and Lee [11] studied the filling process by a modified volume of fluid method based on four node elements in 2D geometry. Tseng et al. [12] calculated the fluid filling into micro-fabricated reservoirs by VOF and CSF (continuum surface force model).

As the molten salt is filled into a cold pipe, the solidification phenomena appear as the temperature of the molten salt drops below the freezing point. After the whole pipe is filled with molten salt, the melting phenomena appear because the high temperature fluid can heat the solidification layer. Therefore, the solidification and melting phenomena play an important role in the molten salt filling process. Bergmann et al. [13] proposed a mathematical model to investigate the cooling and rapid solidification of molten metal droplets by introducing this model into a standard two phase flow simulation model for the spray cone description. Im et al. [14] conducted a unified analysis on the filling and solidification in casting with natural convection. Kalaiselvam et al. [15] studied the solidification and melting characteristics of PCMs inside cylindrical encapsulation. Lu and Ding [22] investigated the dynamical

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Nomenclature

A	flow resistance (m/s)
A_{mush}	mushy zone constant (kg m^{-3} s^{-1})
c	thermal capacity (J kg^{-1} K^{-1})
E	apparent energy (J/kg)
f	content of solid or liquid phase (–)
g	gravity acceleration (m s^{-2})
H	latent heat (J/kg)
h	heat transfer coefficient (W m^{-2} K^{-1})
P	pressure (Pa)
q	heat flux (W m^{-2})
R_1	inner pipe radius (m)
R_2	outer pipe radius (m)
T	temperature (K)
t	time (s)
u	velocity (m/s)
$\overline{v}$	velocity vector (m/s)
x, y, z	coordinate (m)

Greek symbols

α	volume fraction (–)
ρ	density (kg m^{-3})
σ	surface tension (N/m)
λ	thermal conductivity (W m^{-1} K^{-1})
μ	viscosity (kg m^{-1} s^{-1})

Subscripts

0	inlet condition
g	gas
l	liquid phase
m	molten salt
s	solid phase
n	natural convection

and thermal performance of molten salt pipe during filling process without phase change.

Available articles have experimentally reported the solidification and melting phenomena during the filling process in molten salt system, but the evolution behaviors and heat transfer performances of the solidification and melting process have not been further studied. Hence, numerical models for multiphase flow and liquid-solid phase change will be proposed to investigate the solidification and melting behaviors and characteristics of molten salt during the cold filling process in present article. The filling process is simulated using volume of fluid model, and the solid and liquid phases of molten salt during phase change are calculated by linear method. The basic solidification and melting phenomena during the filling process are first described, and then associated dynamic and thermal performances including the pressure loss evolution and heat flux distribution are reported. In additional, the dynamical and thermal performances of the filling process are further compared and analyzed under different inlet temperatures and velocities.

2. Physical and mathematical model

In order to investigate the solidification and melting behaviors of the molten salt, the cold filling process will be studied in a straight cold pipe with molten salt flow of constant inlet temperature and velocity. As illustrated in Fig. 1, the filling process is studied in a 3-D straight circular pipe made of steel, and its inner and outer radii are respectively R_1 and R_2. The pipe wall temperature at the inlet is T_0, while the pipe wall at the outlet is insulated. The heat transfer coefficient of the natural convection outside the pipe is h, and the surrounding temperature is T_s. At the initial time, the molten salt with temperature T_0 and velocity u_0 is filled in the cold pipe.

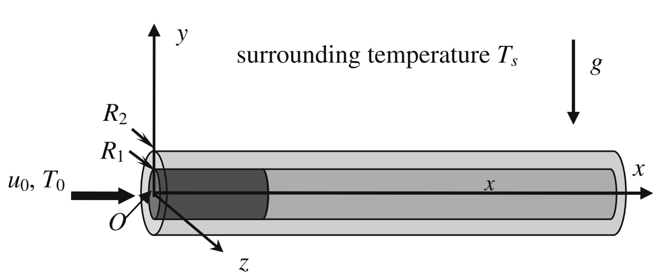

Fig. 1. The basic physical model of the filling process.

Since the filling process is a multiphase problem, it is simulated using volume of fluid (VOF) model [20], and the interface between molten salt and gas is calculated by the continuum surface force (CSF) model [21]. The continuity equations for the molten salt and gas phases are:

$$\frac{\partial \alpha_m}{\partial t} + \overline{v}\nabla\alpha_m = 0, \tag{1a}$$

$$\frac{\partial \alpha_g}{\partial t} + \overline{v}\nabla\alpha_g = 0, \tag{1b}$$

where α_m and α_g denotes the content of the molten salt and gas, and $\alpha_m + \alpha_g = 1$, $\overline{v} = \alpha_m\overline{v_m} + \alpha_g\overline{v_g}$, $\overline{v_m}$ and $\overline{v_g}$ denotes the velocity of the molten salt and gas.

The momentum equation is:

$$\frac{\partial(\rho\overline{v})}{\partial t} + \nabla(\rho\overline{v}\overline{v}) = -\nabla p + \nabla[\mu(\nabla\overline{v} + \nabla\overline{v}^T)] - A - \rho g \cdot j, \tag{2}$$

where $\rho = \alpha_m\rho_m + \alpha_g\rho_g$, A means the momentum sink in the mushy zone of molten salt, g denotes the gravity acceleration, and j is the vertical vector.

The energy equation is given as:

$$\frac{\partial(\rho E)}{\partial t} + \nabla[\overline{v}(\rho E + p)] = \nabla\cdot(\lambda\nabla T) + Q, \tag{3}$$

where $\lambda = \alpha_m\lambda_m + \alpha_g\lambda_g$, $\mu = \alpha_m\mu_m + \alpha_g\mu_g$, $E = \frac{\alpha_m\rho_m E_m + \alpha_g\rho_g E_g}{\alpha_m\rho_m + \alpha_g\rho_g}$, and Q is the heat generation caused by the phase change.

The molten salt zone with solid and liquid phases can be described as:

$$f_l = 1 \quad \text{as } T > T_l, \tag{4a}$$

$$f_l = \frac{T - T_s}{T_l - T_s} \quad \text{as } T_s \leqslant T \leqslant T_l, \tag{4b}$$

$$f_l = 0 \quad \text{as } T < T_s, \tag{4c}$$

where f_l and $f_s = 1 - f_l$ denotes the content of solid and liquid phases in the molten salt zone. The momentum sink in the mushy zone of molten salt is [16,20]:

$$A = \alpha_m \frac{A_{mush}(1 - f_l)^2}{(f_l + \varepsilon)^3}\overline{v_m}, \tag{5}$$

where A_{mush} means the mushy zone constant, ε is a small number (0.001) to prevent division by zero. The mushy zone constant measures the amplitude of the damping; the higher this value, the stee-