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Migration and phase change phenomena and characteristics of molten salt leaked into soil porous system

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ABSTRACT

Molten salt is important heat transfer and storage medium in various high temperature industrial systems, but its leakage and pollution have been seldom investigated. In this paper, migration and phase change phenomena and characteristics of molten salt leaked into soil porous system are numerically investigated using volume of fluid model. During the leakage stage, molten salt expands above the soil, migrates inside the soil and begins to solidify, and finally it solidifies as a solid layer during the post-leakage stage. The vertical velocity of molten salt inside the soil linearly decreases near the surface during the leakage stage, so molten salt gradually migrates into the soil, while the whole flow velocity rapidly approaches to zero after leakage. The temperature and heat flux in the soil near the surface both increase during the leakage stage, and then they decrease during the post-leakage stage. Because of solidification, there exist maximum migration radius and migration depth, so the environment pollution can be limited. As the inlet temperature rises, the maximum migration radius and migration depth both increase for low viscosity of molten salt, while the inlet velocity increment only increases the maximum migration radius. As the soil porosity or particle diameter increases, the maximum migration radius decreases, while the maximum migration depth increases.

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1. Introduction

Molten salt [1,2] is widely used as heat transfer and storage medium in solar thermal power and other industrial systems. Molten salt is generally composed of two or more inorganic salts, and it has many advantages such as large heat capacity, low melting point, low viscosity and chemical stability at high temperature. The environmental pollution caused by molten salt is also an important problem for its application, and it mainly includes the release of nitrogen oxides under high temperature condition [3,4] and molten salt migration in the soil/groundwater after leakage [5].

In some extreme conditions like pipe/storage breakage, molten salt is leaked into the soil, and molten salt pollution in the soil and groundwater will be a serious problem. The leaked molten salt will flow above and into the soil, and the molten salt and air both play an important role in flow dynamic and heat transfer, so the molten salt leakage process is an unsteady multiphase flow. Various numerical methods [6,7] including VOF (Volume of fluid), CSF (continuum surface force model), and phase field method have been applied to investigate these kinds of multiphase processes. Tseng et al. [8] calculated the fluid filling into micro-fabricated reservoirs by VOF and CSF. Lu et al. [9] simulated the dynamic and thermal performance of filled molten salt by VOF. Dawson et al. [10] used the moving boundary model to simulate the growth of crystalline deposits from undetected leakages of industrial process liquors.

As the molten salt is leaked into the soil, the temperature of molten salt will drop below the freezing point, so phase change phenomena such as solidification play important roles in the molten salt leakage process. Researchers have investigated the phase change of molten salt during filling process. Pacheco and Dunkin [11] studied the freeze-up and recovery events of a molten salt receiver, and reported the phase change phenomena of molten salt. Lu et al. [12] numerically studied the solidification and melting behaviors and characteristics of molten salt in cold filling pipe. Liao et al. [13] simulated phase change of molten salt during the cold filling of a receiver tube. The phase change of molten salt/metal during its preparation process has been also studied. Bergmann et al. [14] proposed a standard two phase flow simulation model to investigate the cooling and rapid solidification of molten metal droplets. Im et al. [15] analyzed the solidification phenomena in casting.

When the leaked molten salt is dissolved by the rain or other water flow, it will migrate into the soil and groundwater. Available

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Nomenclature

A	flow resistance (kg m^{-2} s^{-2})
A_{mush}	mushy zone constant (kg m^{-3} s^{-1})
C_2	inertial loss coefficient (–)
c_p	thermal capacity (J kg^{-1} K^{-1})
D_p	particle diameter (m)
f	content of solid or liquid phase (–)
g	gravity acceleration (ms^{-2})
H	depth (m)
H_{sl}	latent heat (J/kg)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
P	pressure (Pa)
q	heat flux (W m^{-2})
R	radius (m)
S_h	heat source (W m^{-3})
S_m	momentum source (kg m^{-2} s^{-2})
T	temperature (°C)
t	time (s)
t_w	the whole leakage time (s)
u	velocity (m/s)
$\bar{u}$	velocity vector (m/s)
y	coordinate (m)

Greek symbols

α	volume fraction, permeability (–)
ε	porosity (–)
ρ	density (kg m^{-3})
σ	interface tension (N/m)
γ	small number (–)
μ	viscosity (kg m^{-1} s^{-1})

Subscripts

0	inlet condition
aet	average external thickness
amd	average migration depth
eff	effective
f	fluid
g	gas
in	inlet
l	liquid phase
m	molten salt
mmd	maximum migration depth
mmr	maximum migration radius
n	natural convection
s	solid phase, surrounding condition

researchers have studied the migration of nitrate. Crevoisier et al. [16] simulated the water and nitrogen transfer under furrow irrigation. Wang et al. [17] detected the leaching of nitrate under heavy rainfall, high irrigation rate in growing season and with different amounts of initial accumulated Peng et al. [18] investigated nitrate migration with waters due to nitrogen fertilizer transformation in paddy soils. Ramos et al. [19] successfully simulated water and solute transport in soils, in which water with different salinity and nitrogen concentrations was used.

Available articles have respectively studied the phase change of molten salt and migration of salt as solute, but the migration and phase change of molten salt leaked into soil porous system have been seldom studied. Hence, numerical model is proposed to investigate the dynamic behaviors and thermal characteristics of molten salt leaked into soil in present article. The multiphase flow process is simulated using volume of fluid model, and the solid and liquid phases of molten salt during phase change are calculated by considering mushy zone, while the soil is assumed as homogeneous porous medium. The basic migration and solidification phenomena of molten salt during the leakage and post-leakage stages are first described, and then associated dynamic and thermal performances including the flow field, temperature and heat flux are reported. In addition, the maximum migration radius and migration depth are further analyzed under different operating conditions and structural parameters, and the environmental pollution of molten salt under dry condition can be estimated.

2. Physical and mathematical model

In order to investigate the migration and phase change phenomena of molten salt leaked into the soil, an axial symmetrical system will be studied. As illustrated in Fig. 1, the whole system is a cylinder, and it mainly includes the soil region and the air region above the soil. The radius of the cylinder is R_1, and the heights of the air region and soil region are respectively H_1 and H_2. The inlet with radius of R_2 is set in the top of cylinder. Convection exists in the air boundary, and the heat transfer coefficient and surrounding temperature are respectively h and T_s. The temperature of the soil bottom is equal to the surrounding temperature T_s. At the initial time, the molten salt with temperature T_{in} and velocity u_{in} is leaked from the inlet, and the whole leakage time is t_w. After molten salt is leaked, it first drops from the inlet to the soil, then expands above the soil and migrates inside the soil, and it gradually solidifies with its temperature decreasing.

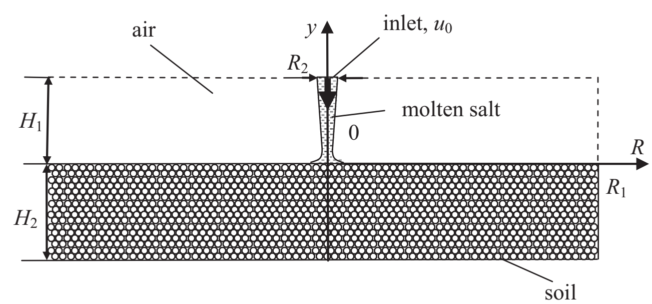

Fig. 1. The physical model of molten salt leakage system.

Since the leakage 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 [20]:

$$\frac{\partial \alpha_m}{\partial t} + \vec{u} \cdot \nabla \alpha_m = \frac{S_{\alpha_m}}{\rho_m} \tag{1a}$$

$$\frac{\partial \alpha_g}{\partial t} + \vec{u} \cdot \nabla \alpha_g = \frac{S_{\alpha_g}}{\rho_g} \tag{1b}$$

where α_m and α_g denote the contents of the molten salt and gas, and $\alpha_m + \alpha_g = 1$, $\vec{u} = \alpha_m \vec{u}_m + \alpha_g \vec{u}_g$, $\vec{u}_m$ and $\vec{u}_g$ denote the velocities of the molten salt and gas, S_{α_m} and S_{α_g} denote source terms for the contents of molten salt and gas.

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