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Numerical investigation of vapor–liquid heat and mass transfer in porous media

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ABSTRACT

A modified separate flow model (MSFM) is developed to numerically investigate the heat and mass transfer behaviors in porous media in this paper. In the MSFM, the effects of capillarity, liquid phase change, nonisothermal two-phase region and the local thermal non-equilibrium (LTNE) are considered. The vapor and liquid velocities are both converted into intermediate variables in the simulations and conveniently convergent solutions are obtained because a special upwind scheme for the convection or boiling heat transfer source and variable convergence factors are simultaneously employed. Two typical numerical examples with a one-dimension model of porous media are studied that the high heat fluxes are vertical and parallel to the fluid flow direction, respectively. And the results indicated that the influence of heat flux direction on heat and fluid flow behaviors in porous media is great. The nonisothermal phenomenon in the two-phase region is obvious for the former while the LTNE phenomenon is remarkable in the two-phase region for the latter. The results also showed several similar behaviors that the saturation profile is weakly discontinuous on the phase interface and a countercurrent flow exists in two-phase region.

1. Introduction

Heat transfer and two-phase flow in porous media has attracted lots of interest in many diverse fields such as transpiration cooling, petroleum engineering, energy storage and recovery, nuclear waste disposal, heat pipes, drying of porous media in recent years [1–4]. The interstitial fluids in porous media are usually subject to vaporization, condensation and transport due to pressure or temperature gradients. Because of the small pore dimensions and extremely complex pore geometry, the interfacial tension effect is obvious that the system variables such as individual phase pressures, liquid–vapor interfacial geometry, and fluid velocities on the pore level is difficult to obtain. To solve this problem, the macroscopic averaging of microscopic phenomena, namely upscaling technology can be used. There are several different ways of up-scaling for dispersion in porous media, such as the volume average method [5], the homogenization method [6], the ensemble average method [7] and the method of moments [8], and so on. As the equations based on up-scaling technology are often suitable to spatially periodic geometric structure but accompanied with the closure problem, the semi-experiential separate flow model (SFM) [9]and two-phase mixture model (TPMM) [10] which are also based on macroscopic parameters like the conservation equations based on up-scaling technology are widely used in simulations in porous media.

Experimental observations [11] were reported on boiling in a vertical circular by heating from below and cooled from above and it was found that the liquid and vapor counter percolation could carry heat across the two-phase zone (the liquid evaporated at the heating surface and the vapor condensed at the boundary between the liquid zone and two-phase zone) and the two-phase zone was nearly isothermal. Heat and mass transfer characteristics of a sand-steam system heated at the top and cooled at the bottom were investigated by Udell [12,13] and it was also indicated that the temperature was nearly isothermal in the two-phase region. Topin et al. [14] and Rahli et al. [15] conducted experiments in porous media composed of small bronze spheres and heated from the side, and it was demonstrated that the temperature in the two-phase zone was seen to decrease with an N-shaped curve, and the reasons were probably the combined effects of flow and phase-change. Numerical investigations have also been reported. The separate flow model (SFM) was described by Bear [9] to solve the two-phase problems in porous media. In the SFM, the two phases are considered as distinct fluids, which results in a large number of governing equations, and they are computationally burdensome [10,16]. Ramesh and Torrance [17] successfully solved the SFM by the front-tracking method, in which compared with the front-capturing method the mesh reconstruction was necessary to determine the interface between different phases. To avoid mesh reconstruction at every iteration step the two-phase mixture

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Nomenclature

ε	porosity
s	liquid saturation
ρ	density (kg/m^3)
c_p	specific heat capacity (J/kg K)
u	velocity (m/s)
t	time (s)
h	specific enthalpy (J/kg)
Q_{sf}	convection or boiling heat flow (J/m^3 s)
Q_{boil}	boiling heat flow (J/m^3 s)
Q	volumetric heat source (J/m^3 s)
T	temperature (K)
σ	interfacial tension (N/m)
J	capillary J-function
K_r	relative permeability
μ	dynamic viscosity (kg/ms)
K	permeability
k	heat conductivity (W/mK)
Nu	Nusselt number
Re_p	Reynolds number in porous media
Pr	Prandtl number
d_p	hydraulic diameter (m)
α_{sf}	aspect ratio
q	heat flux (J/m^2 s)
h_{lg}	latent heat (J/kg)
h_{sv}	heat transfer coefficient of vapor (W/m^2 K)
h_{sl}	heat transfer coefficient of liquid (W/m^2 K)
g	acceleration of gravity (m/s^2)

Subscripts

s	solid
r	relative
f	fluid
l	liquid
v	vapor
p	pressure
c	capillary pressure
sat	saturated
eff	effective

model (TPMM) and the modified SFM were developed based on the front-capturing method. The TPMM was initially developed by Wang and Beckermann [10]. It is widely used, but it is based on the assumptions that the two-phase region is isothermal and the local temperature of fluid and solid is the same at each point. And the two-phase region temperature used in the TPMM was often determined by the inlet or outlet pressure [18,19]. Under the assumptions, numerical computations may be greatly simplified but may cause larger errors [14,15]. Hence, a new front-capturing method still based on the TPMM was developed by Bridge and Wetton [20]. However, in the model the liquid-only region was not considered and this staircasing phenomenon of temperature at the same point needs further investigations. Based on an entropy balance in the energy equation, Benard et al. [21] presented a new model in which phase region judgements were used to capture the front with saturation equation supplemented. However, the supplemented equation is not necessary in some sense and can increase the time and space complexity for numerical simulations. Based on the SFM idea, Stubos et al. [22] developed a one-domain formulation, in which Kelin and Clapeyron equations were employed in the two-phase region.

The models mentioned above are all based on the local thermal equilibrium assumption that fluid temperature is locally equal to solid temperature. Though this assumption can simplify numerical simulations, it may be inadequate for a number of problems. Shi and Wang [23] and Yuki et al. [24] numerically investigated the two-phase flow in porous media at high heat fluxes, and found that the local thermal non-equilibrium (LTNE) phenomena considering the difference in temperature between the fluid and the solid were remarkable especially in the two-phase region. However, they were both based on the TPMM instead of SFM. In this paper, the front-capturing method is employed that phase regions are judged according to the relations between fluid temperature and saturation temperature. A modified SFM (MSFM) considering the LTNE was developed in the simulations. Both the vapor and liquid velocities are converted into intermediate variables. The function of the primary variables and a special upwind scheme for the convection or boiling heat transfer source and Newton's linear algorithm are both employed.

2. Model and method

2.1. Model

The total mass conservation of fluid phase in porous media can be described as:

$$\varepsilon\frac{\partial(\rho_l s+\rho_v(1-s))}{\partial t}+\nabla\cdot(\rho_l\vec{u}_l+\rho_v\vec{u}_v)=0, \tag{1}$$

where ε, s, ρ and u represent porosity, saturation, density and superficial velocity, respectively.

The LTNE equations considering the local convection or boiling heat exchange between the solid and fluid are following:

$$\varepsilon\frac{\partial}{\partial t}[\rho_l s h_l+\rho_v(1-s)h_v]+\nabla\cdot(\rho_l\vec{u}_l h_l+\rho_v\vec{u}_v h_v) = \nabla\cdot(k_{f,eff}\nabla T_f)+Q_{sf}, \tag{2}$$

$$(1-\varepsilon)c_p\frac{\partial T_s}{\partial t}=\nabla\cdot(k_{s,eff}\nabla T_s)-Q_{sf}+Q, \tag{3}$$

where h, Q_{sf} and Q are specific enthalpy, convection and boiling heat flow per volume and volumetric heat source, respectively.

The capillary pressure satisfies [25]:

$$p_c=p_v-p_l=\left(\frac{\varepsilon}{K}\right)^{1/2}\sigma J(s), \tag{4}$$

where, σ is vapor–liquid interfacial tension, and $J(s)$ is suggested by Udell [13] as:

$$J(s)=1.417(1-s)-2.120(1-s)^2+1.263(1-s)^3. \tag{5}$$

In porous media, there will be potential three different regions for the fluid phase under different conditions:

(I) A region only with liquid water.
(II) A region only with vapor.
(III) A region where water and vapor coexist. In this region, vapor pressure relies on both temperature and vapor-water capillary pressure, therefore the relation [25] is used: