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Numerical investigation of two-phase flow in anisotropic porous evaporator

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ABSTRACT

This work deals with modelling and numerical simulation of complete evaporation process inside anisotropic porous media. Based on the modified enthalpy formulation of Two-Phase Mixture Model (TPMM) along with the assumption of Local Thermal Non-Equilibrium (LTNE), a modified formulation has been proposed that can easily accommodate the anisotropy in the porous media properties. The governing equations have been solved using the Finite Volume Method (FVM) on staggered grid layout. The simulations have been carried out by applying the proposed smoothing algorithm for the effective diffusion coefficient in order to avoid the non-physical jump in the predicted temperature distribution during the numerical simulations. The effects of the permeability ratio, solid thermal conductivity ratio, thermal conductivity of the solid phase and the Darcy number have been investigated. The computed results show that the anisotropy of permeability and thermal conductivity of the solid phase have significant effect on the initiation and termination of phase change process. It is also observed that the anisotropic properties of the porous medium have significant influence on the flow behaviour and heat transfer rate from that expected under isotropic conditions. The results indicated that the effect of thermal conductivity of the solid phase plays an important role and hence adequate care must be taken while designing such evaporators. The results also show that the smoothing algorithm is successful in dealing with the rapid change in the effective diffusion coefficient during the simulations of complete evaporation process.

1. Introduction

Phase change problems inside porous media arise in a substantial number of scientific and engineering applications for the past four decades [1–7]. Furthermore, the attractiveness of porous media lies in the contemporary and wide applications available today, which have led to numerous investigations in this area. Most often, multiphase flows inside porous media are driven by a complex interaction of gravitational, capillary and viscous forces [8]. Understanding the fluid flow and heat transfer associated with phase change in such systems is of fundamental interest. Two-phase flow through porous media has been traditionally solved employing different idealisations, e.g., Separate Flow Model (SFM)[1] [9,10], Separate Phase Model (SPM) [11,12], and Two-Phase Mixture Model (TPMM)[2] [13–15]. The practical applications of the SPM (or SFM) are difficult due to the interface tracking using a moving boundary approach and large number of coupled non-linear equations. Owing to the generality and the simplicity of the numerical formulation, TPMM of Wang [15] has been most often used for the simulation of two-phase flow inside porous media.[3] In this model, the separate phases are viewed as the constituents of a binary

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[1] SFM is extremely complex and inconvenient for direct use in numerical simulation due to the strongly nonlinear and coupled nature of differential equations that must be solved.

[2] The model of Wang and Beckermann [13] is not readily suitable for numerical implementation, since the volumetric enthalpy is not monotonic function of the thermodynamic state during transition from single-phase to two-phase zone.

[3] This model is characterized by the coexistence of a two-phase zone and single-phase regions with irregular, as well as moving interfaces lying in between them.

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Nomenclature

a_s	Specific surface of the porous medium, 1/m
$\mathbf{b}$	Body force vector per unit mass, m/s^2
$\tilde{\mathbf{b}}$	Normalized body force vector per unit mass = $\mathbf{b}/g$
C_p	Specific heat, J/kgK
d_p	Characteristic pore size of porous matrix, m
D	Capillary diffusion coefficient, m^2/s
f	Hindrance function
Fr	Froude number = $u_{in}/u_g = u_{in}/\sqrt{g\ W} = Re_{in}/Re_g$
$\mathbf{g}$	Acceleration due to gravitational vector, m/s^2
h	Specific enthalpy, J/kg
h_{fg}	Latent heat of vaporization = $h_{v,sat} - h_{l,sat}$, J/kg
$h_{s\alpha}$	Convective heat transfer coefficient in the pores, W/m^{2}K
$\mathbf{j}$	Diffusive mass flux vector, kg/m^{2}s
J	Capillary pressure function
k_{rl}, k_{rv}	Relative permeabilities for liquid and vapour, respectively
k	Thermal conductivity, W/mK
k_R	Thermal conductivity ratio= k_{sy}/k_{sx}
K	Permeability of porous matrix, m^2
K_R	Permeability ratio = K_{yy}/K_{xx}
l	Length of individual segments, m
L	Length of the porous channel, m
n	Exponent of saturation in the expression for relative permeabilities
N_{CV}	Number of employed control volumes
p	Effective pressure, Pa
p_c	Capillary pressure, Pa
Pe	Peclet number = $u_{in}W/\alpha = RePr$
Pr	Prandtl number = $\mu\ C_p/k$
$\dot{q}''$	Heat flux, W/m^2
Q^*	Normalized heat flux = $\dot{q}''W/\mu h_{fg}$
$\dot{q}_{sf}$	Heat exchange term between fluid and solid phases, W/m^3
Re	Reynolds number = $u_{in}W/\nu$
Re_g	Gravitational Reynolds number= $u_g W/\nu_l$
Re_p	Reynolds number based on pore diameter and local phase properties
Re_K	Fluid Reynolds number based on the length scale of the permeability
s	Liquid saturation
T	Temperature, K
$\mathbf{u}$	Velocity component vector, m/s
u_g	Gravitational velocity vector $\sqrt{\mathbf{g}\ W}$, m/s
W	Height of the duct, m
x, y	horizontal and vertical Coordinates, respectively, m

Greek Symbols

α m^2/s	Thermal diffusivity = $k/\rho\ C_p$,
β	Isobaric expansion coefficient, K^{-1}
ΔT	Temperature difference for relaxation of Γ_h is in the single-phase regions, K
$\Delta\rho$	Difference in densities= $(\rho_l - \rho_v)$, kg/m^3
γ_h	Advection correction coefficient
Γ_h	Diffusion coefficient in enthalpy equation, kg/m.s
ε	Porosity
λ	Relative mobility
μ	Dynamic viscosity, kg/ms
ν	Kinematics viscosity, m^2/s
ρ	Density, kg/m^3
σ	Surface tension, N/m
$\tilde{\sigma}$	Normalized surface tension coefficient = $\dot{q}''W/\mu h_{fg}$

Subscripts

eff	Effective
f	Fluid
i, e, h	Inlet, exit and heated, respectively
in	Inlet
k	Kinetic
l	Liquid
max	Maximum value
min	Minimum value
s	Solid
sat	Saturation
v	Vapour
w	Wall

Superscripts

*	Dimensionless

mixture. In addition, the TPMM of Wang [15] is more convenient than the TPMM of Wang et al. [14],[4] for complete evaporation process and is widely used in order to solve the two-phase flow problems within isotropic porous structure to enhance the knowledge of two-phase flow inside porous media [16–22].

As far as the energy conservation equation is concerned, two different idealizations according to homogenisation approach could be employed for different applications involving flow through porous media: Local Thermal Equilibrium (LTE) and the Local Thermal Non-Equilibrium (LTNE) models. Both these models can be applied for the complete evaporation process inside porous media based on TPMM of Wang [15]. As the name suggest, under the assumption of LTE, the heat exchange between the working fluid and the solid matrix of the porous medium is neglected[5] [13–22]. The assumption of LTE between the solid and the fluid-phases is inadequate for several reasons as explained later. On the other hand, in order to consider the internal heat transfer between the fluid and solid phases within the porous matrix, the LTNE model has to be applied, where two separate energy conservation equations for both phases are solved. These two equations are, however, coupled to each other through the internal heat exchange term. Wang and Wang [23] performed a study to measure the error caused by the LTE assumption, where, in principle, LTNE model should have been employed, although, they did not comment on the applicability of LTE model for two-phase problems. However, serious attention is paid to LTNE model in the recent years as it helps in better understanding of the mechanisms responsible for the overall heat transfer during the phase ch ange process inside porous media [24–27]. In this respect, the use of LTNE model is quite common in many other applications of porous media, for example, combustion inside porous media [28–30].

However, a major problem that is encountered during the simulation of complete evaporation process is the occurrence of drastic, non-

[4] The model of Wang et al. [14], however, fails to predict the transition from the two-phase to the vapour phase, since some of the variables (properties) remain undefined for the vapour phase.

[5] The TPMM of Wang [15] considers that the temperature difference between the solid- and the fluid-phase at any location is neglected.