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Numerical simulation of complete liquid–vapour phase change process inside porous media: A comparison between local thermal equilibrium and non-equilibrium models

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ABSTRACT

The Complete liquid-vapour phase change process inside an asymmetrically heated porous channel has been numerically investigated in this article, based on the Two-Phase Mixture Model (TPMM), while employing both Local Thermal Equilibrium (LTE) and Non-Equilibrium (LTNE) conditions. For the latter condition, four different models have been considered for the partitioning of imposed wall heat flux. All simulations have been carried out by applying the recently proposed smoothing algorithm for the effective diffusion coefficient, without which, the occurrence of non-physical "jump" in the predicated properties, across the interface between the single and the two-phase regions could not be always avoided. The governing equations have been discretised using the finite volume method on a fixed staggered grid layout and solved iteratively in a SIMPLE-like manner. Only the imposed wall heat flux has been varied, while all other parameters and properties have been kept fixed during the present investigation. It has been observed that LTE model fails to produce realistic predictions, particularly when the superheated vapour phase is formed inside the evaporator. On the other hand, the conduction heat transfer through the solid phase and the internal heat exchange between the solid and the fluid phases across the interface separating the superheated vapour and the two-phase mixture regions provide two additionally required mechanisms for LTNE model for the realistic predictions. As far as different models for the partitioning of wall of heat flux is concerned, Model-2 appears to be the most realistic, while Model-1 has been found to be the most stable.

1. Introduction

Liquid-vapour phase change processes within porous media occur in a wide variety of applications [1–11], where they are most often driven by a complex interaction of gravitational, capillary and viscous forces [12]. Two-phase flow within porous media could be theoretically described by the Separate Flow Model (SFM) [3,4] where the liquid and the gaseous phases are identified as distinct fluids. Following a similar approach, Ramesh and Torrance [13,14] proposed the Separate Phase Model (SPM) in order to solve problems involving boiling in presence of natural convection in a fluid-saturated porous medium. For practical situations, however, SFM (or SPM) is considered inconvenient since it requires tracking of the interfaces using a moving boundary approach.

In order to eliminate the difficulties associated with SFM, several variants of the Two-Phase Mixture Model (TPMM) were proposed [15–17], where the separate phases are considered as the constituents of a binary mixture and the solutions could be obtained on a fixed grid, without requiring a priori knowledge of

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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
$\tilde{\mathbf{b}}$	Normalised 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 $= u_{in}/u_g = u_{in}/\sqrt{gW} = Re_{in}/Re_g$
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
H	Modified volumetric enthalpy $= \rho(h - 2h_{v,sat})$, J/m^3
$\mathbf{j}$	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	Permeability of porous matrix, m^2
l	Length of individual segments, m
L	Length of the porous channel, m
n	Exponent of saturation in the expression for relative permeabilities
p	Effective pressure, Pa
Pe	Peclet number $=u_{in}W/\alpha = RePr$
Pr	Prandtl number $=\mu C_p/k$
$\dot{q}''$	Heat flux, W/m^2
$\dot{q}'''_{sf}$	Heat exchange term between fluid and solid phases, W/m^3
Re	Reynolds number $=u_{in}W/\nu$
Re_g	Gravitational Reynolds number$=u_gW/\nu_l$
Re_p	Reynolds number based on pore diameter and local phase properties
s	Liquid saturation
T	Temperature, K
$\mathbf{u}$	Velocity vector, m/s
u_g	Gravitational velocity $\sqrt{gW}$, m/s
W	Height of the duct, m
x,y	horizontal and vertical Coordinates, respectively, m

Greek symbols

α	Thermal diffusivity $=k/\rho C_p$, m^2/s
β	Isobaric expansion coefficient, K^{-1}
$\Delta\rho$	Difference in densities $= (\rho_l - \rho_v)$, kg/m^3
γ_h	Advection correction coefficient
Γ_h	Diffusion coefficient in enthalpy equation, m^2/s
ε	Porosity
λ	Relative mobility
μ	Dynamic viscosity, kg/ms
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
σ	Surface tension coefficient, N/m
$\tilde{\sigma}$	Normalised surface tension coefficient $=\rho_l\sigma W/\mu_l^2$

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

the phase boundaries, that could be irregular in space as well as moving in time. In this respect, the second modification of TPMM [17] has been proved to be extremely popular and hence widely used for the simulation of phase change problems inside porous media [18–24].

According to the homogenization approach, two different idealisations could be employed as far as the temperature field is concerned. For the Local Thermal Equilibrium (LTE) condition, the solid and the fluid phases are assumed to locally coexist at the same temperature and hence the total energy conservation equation is employed for both phases. On the other hand, under the assumption of Local Thermal Non-Equilibrium (LTNE) condition, the solid and the fluid phase temperatures are assumed to differ at a given location. Therefore, separate energy conservation equations are derived for each phase that are coupled to each other through the volumetric heat exchange term. Both these models can be applied for the simulation of phase change process inside porous media, although all original variants of TPMM [15–17] rely upon the assumption of LTE condition. In recent years, however, serious attention has been paid to LTNE model since it is more realistic for the local solid-fluid energy transfer [25–29]. For single-phase problems, Wang and Wang [30] performed a study in order to quantify the errors caused by LTE assumption, although they did not comment on its consequences for the phase change problems. The use of LTNE model, however, is quite common in many other applications, for example, combustion inside porous media [31–33].

For practical phase change problems inside porous media, the thermal conductivity of the solid matrix is substantially higher than that of the working fluid. Therefore, heat that is supplied at the evaporator surface is transferred to the fluid primarily through the solid struts. Particularly in the two-phase region, since the fluid temperature remains constant owing to the thermodynamic constraint, the energy transfer from the heated wall is dominated by heat conduction through the solid medium. The solid and fluid temperatures in this region differ from each other, although the difference may not be substantial, since the volumetric heat exchange coefficient could be extremely high owing to the small characteristic pore diameter [29]. In this situation, LTNE condition would be more appropriate and hence it would be worthwhile to