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Simulation of complete liquid–vapour phase change process inside porous evaporator using local thermal non-equilibrium model

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ABSTRACT

The present article demonstrates the necessity and the usefulness of a newly proposed smoothing algorithm for the effective diffusion coefficient in order to avoid non-physical "jump" in the predicted properties during numerical simulations of the complete liquid–vapour phase change process within porous media. The formulation is based on the two-phase mixture model (TPMM) along with the assumption of local thermal non-equilibrium (LTNE) condition where the governing equations have been solved using the finite volume method. For the purpose of demonstration, one-dimensional phase change problem of water has been considered. Comparison between results obtained with the local thermal equilibrium (LTE) and LTNE models indicates that wherever applicable, particularly for lower inlet Reynolds number and higher heat input, the latter should be used. The effect of employing different models for the partitioning of wall heat flux using LTNE model has been found negligible owing to the very high convective heat transfer coefficient between the solid and the fluid phases. A representative parametric study suggests that the diffusive energy transport process in the upstream direction through the solid and the fluid phases has a strong influence on the initiation and the termination of the phase change process.

1. Introduction

Liquid-vapour two-phase flow through porous media is important in several engineering applications [1] which has been solved over the years employing different idealisations, e.g., separated flow model [2,3], separated phase model [4,5] and Two-Phase Mixture Model (TPMM) [6–8]. In TPMM, both phases are viewed as the constituents of a binary mixture and the model is characterised by the coexistence of a two-phase zone and single-phase regions with irregular interfaces lying in between them that can even move for transient problems.[1] TPMM of Wang [8], which is regarded as the second modification to the original proposal of Wang and Beckermann [6], consists of a specifically derived energy conservation equation in terms of the modified volumetric enthalpy other than the conventional mass and the Darcy momentum equations. Since this model is more convenient than others, it is widely used for simulating phase change problems inside porous media [9–15].

As far as the energy conservation equation for porous media is concerned, two separate models, suitable for different applications, are available according to the homogenisation approach: the local thermal equilibrium (LTE) and the local thermal non-equilibrium (LTNE) models. Both these models can be applied for the complete phase change process inside porous media based on TPMM of Wang [8]. As the name suggests, under the assumption of LTE, the heat exchange between the working fluid and the solid matrix of the porous medium is neglected. On the other hand, in order to consider the internal heat transfer between the fluid and the solid phases, the LTNE model has to be applied, where two separate energy conservation equations for both phases are solved. These

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[1] The model of Wang et al. [7], 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.

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Nomenclature

a_s	specific surface of the porous medium, $1/m$
A_c	cross-sectional area of the pipe per unit radian $=R^2/2$, m^2
b	body force per unit mass, m/s^2
$\tilde{b}$	normalized body force per unit mass $=b/g$
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 $= u_{in}/u_g = u_{in}/\sqrt{g\,R} = Re_{in}/Re_g$
g	acceleration due to gravitational, 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^2K
H	modified volumetric enthalpy, $=\rho(h-2h_{v,sat})$, J/m^3
j	diffusive mass flux, kg/m^2s
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 evaporator, m
m_ϕ, m_s	exponents for smoothing Γ_h in single and two-phase regions, respectively
n	exponent of saturation in the expression for relative permeabilities
p	effective pressure, Pa
P	perimeter of the pipe per unit radian$=R$, m
Pe	Peclet number $=u_{in}R/\alpha=RePr$
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
Q^*	normalised heat flux, $=\dot{q}''R/\mu h_{fg}$
Re	Reynolds number $=u_{in}R/\nu$
R	radius of the evaporator, m
Re_g	gravitational Reynolds number$=u_gR/\nu_l$
Re_p	Reynolds number based on pore diameter and local phase properties
s	liquid saturation
s_l, s_v	cut-off liquid saturations for Γ_h in liquid and vapour phases, respectively
T	temperature, K
u	velocity component, m/s
u_g	gravitational velocity $\sqrt{g\,R}$,m/s
x	axial coordinate, m

Greek Symbols

α	thermal diffusivity $=k/\rho\,C_p$, m^2/s
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
ϕ	normalised temperature for relaxation of Γ_h
γ_h	advection correction coefficient
Γ_h	diffusion coefficient in enthalpy equation, m^2/s
$\Gamma_{h,\phi}$, $\Gamma_{h,s}$	asymptotes for smoothing Γ_h in single and two-phase regions, respectively
ε	porosity
λ	relative mobility
μ	dynamic viscosity, $kg/m\,s$
ν	kinematics viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension coefficient, N/m
$\tilde{\sigma}$	normalized surface tension coefficient $=\rho_l\sigma R/\mu_l^2$
ψ	factor, used to modify Γ_h at saturated condition ($s=0$ and $s=1$)

Subscripts

eff	effective
f	fluid
i, *e*, *h*	inlet, exit and heated, respectively
in	inlet
k	kinetic
l	liquid
s	solid
sat	saturation
x	pertaining to axial direction
v	vapour
w	wall

Superscripts

*	dimensionless

two equations are, however, coupled to each other through the volumetric (convective) heat exchange term. For single-phase problems, Wang and Wang [16] presented a study on the quantitative error caused by the LTE assumption, where, in principle, LTNE model should have been applied, although they did not comment on the applicability of LTE model for the two-phase flow problems.

According to Jiang and Ren [17], the classical LTNE model was first presented approximately 80 years ago. However, serious attention has been paid to LTNE model only in recent years as it helps in better understanding the mechanisms of convective heat transfer during the phase change process inside porous media [18–21]. Nevertheless, the use of LTNE model is quite common in many other applications of porous media, for example, combustion inside porous media [22–24], where the difference between the solid and the fluid temperatures could be substantially high, particularly close to the flame-front, which cannot be neglected in order to explain the mechanism of internal heat recirculation.

In the field of evaporation within porous media, a comprehensive review of literature shows that almost all previous studies dealt with incomplete phase change process (i.e., from the subcooled liquid to the two-phase mixture) using both LTE and LTNE models. According to the best of the present authors' knowledge, only Wang [8] and Shi and Wang [20] numerically investigated the complete phase change assuming the process occurring at a constant (i.e., fixed) saturation temperature.[2] While Wang [8] presented results for the phase change due to localised heat source in a two-dimensional channel using LTE model, Shi and Wang [20] extended the numerical simulations for one-dimensional problem adopting LTNE model. Nevertheless, in both these studies, although

[2] This assumption applies when the pressure drop through the evaporator is negligible as compared to the static pressure for a given saturation temperature, which is valid for low mass flow rate applications.