International Journal of Thermal Sciences 129 (2018) 56–72

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Numerical investigation of complete evaporation process inside porous evaporator using staggered and non-staggered grid arrangements

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ARTICLE INFO

Keywords:
Porous media
Modified enthalpy formulation
TPMM
Complete evaporation process
LTNE model
Staggered and non-staggered grid layouts

ABSTRACT

The complete evaporation process inside an asymmetrically heated porous channel, under steady-state condition, has been numerically investigated in this article, based on the modified enthalpy formulation along with the assumption of Local Thermal Non-Equilibrium (LTNE). The governing equations have been discretised using finite volume method on both staggered and non-staggered grid arrangements and solved iteratively in a SIMPLE-like manner. All 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 distributions. The performance of staggered and non-staggered grid layouts have been compared only on orthogonal coordinates for various parameters and the results show that the accuracy and effectiveness of the non-staggered and staggered grid layouts are identical. Different models for the partitioning of the wall heat flux have no influence on the total evaporated volume fraction. Effects of various parameters on the temperature and liquid saturation distributions have been carefully investigated, which clearly indicate that imposed heat flux, Reynolds number, Darcy number and thermal conductivity of the solid phase strongly influence the initiation and termination of phase change process, whereas the porosity has only a minor impact. Therefore, operating conditions and properties of porous media are required to be properly designed in order to achieve the desired objective. In addition, the results obtained using the modified h- and H-formulations have been compared and excellent agreement have been observed. It has been found that the modified h-formulation requires considerably less computation time as compared to that for the H-formulation and hence the method is strongly recommended for the future use. Nevertheless, it should now be extended in order to accommodate the multi-dimensional complex geometries that require the employment of curvilinear coordinates using non-staggered grid layout.

1. Introduction

Problems involving two-phase flow and heat transfer within porous media arise in a number of scientific and engineering applications [1–8]. Two-phase flow inside porous media, which is based on a continuum formulation where the gaseous and liquid phases are regarded as two distinct fluids, could be theoretically described by the Separate Flow Model (SFM) [9,10]. Following a similar approach, Ramesh and Torrance [11,12] proposed the Separate Phase Model (SPM) in order to solve heat transfer problems involving boiling in presence of natural convection in a fluid-saturated porous medium. For practical applications, however, SFM (or SPM) is considered inconvenient for direct use in numerical simulation due to the interface tracking using a moving boundary approach and large number of coupled nonlinear equations. Recognising the complexities and the inherent problems of SFM, Wang and co-worker [13–15] developed several variants of Two-Phase Mixture Model (TPMM) where the separate phases are viewed as the constituents of a binary mixture. In TPMM, the solutions could be obtained on a fixed grid, without requiring a priori knowledge of the phase boundaries, that could be irregular in space as well as moving in time. Owing to the generality and the simplicity of numerical implementation, TPMM of Wang [15] proved to be extremely popular[1,2] and hence widely used for the simulation of phase change problems inside

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[1] 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.

[2] 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.

https://doi.org/10.1016/j.ijthermalsci.2018.02.022
Received 28 September 2017; Received in revised form 20 February 2018; Accepted 20 February 2018
Available online 10 April 2018
1290-0729/

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
ev	Total evaporated volume fraction
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^2/s
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
p_c	Capillary pressure, Pa
Pe	Peclet number = $u_{in}W/\alpha = RePr$
P_r	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	Thermal diffusivity = $k/\rho\, C_p$, m^2/s
β	Isobaric expansion coefficient, K^{-1}
δx, δy	Nodal distances in the axial and radial directions, respectively, m
ΔT	Temperature difference for relaxation of Γ_h is in the single-phase regions, K
Δx, Δy	Width of the control volume in axial and radial directions, respectively, m
$\Delta\rho$	Difference in densities= $(\rho_l - \rho_v)$, kg/m^3
γ	Advection correction coefficient
Γ	Diffusion coefficient for enthalpy, kg/m s (for h) or m^2/s(for H)
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
$\bar{\sigma}$	Normalized surface tension = $\rho_l\sigma W/\mu_l^2$

Subscripts

e, w, s, n	Pertaining to cell faces at e, w, s and n, respectively
E, W, S, N, P	Pertaining to nodes at E, W, S, N and P, respectively
eff	Effective
h, H	Pertaining to h and H, respectively
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
∧	Guess value
'	Correction value

porous media [16–22].

As far as the energy conservation equation for porous medium is concerned, there are two distinct models available for porous media applications: Local Thermal Equilibrium (LTE) and Local Thermal Non-Equilibrium (LTNE) models. Both these models can be applied in order to investigate the complete evaporation process inside a porous medium, although all original variants of TPMM [13–15] rely upon the assumption of LTE condition.[3] The topic of two-phase flow within a porous medium in rectangular channels with uniform heating conditions is reported in a substantial number of works [14–22], where the LTE model is adopted to perform the numerical investigations. For allowing possible volumetric heat exchange between the solid struts and the working fluid, the LTNE has to be applied, where two energy conservation equations for both phases are solved. Volumetric heat exchange term are added in both equations for this purpose. 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 the mechanisms responsible for the overall heat transfer during the phase change process inside porous media [24–27]. In this regard, the use of LTNE model is quite common in many other applications of porous media, as for example in combustion inside porous media [28–30].

However, a major problem that is encountered during the simulation of complete phase change process is the occurrence of drastic, non-physical change in the predicted properties over an extremely short distance[4] that results primarily due to the presence of discontinuities in the effective diffusion coefficient for the saturated liquid and vapour phases. Recognising this problem, different researchers [21,22,27,31–33] addressed this issue by either modifying the manner

[3] For LTE model, the solid and the fluid phases are assumed to locally coexist at the same temperature. The volumetric heat exchange term between the working fluid and the solid matrix of the porous medium is neglected and hence the total energy conservation equation is employed for both phases.