



Simulation of liquid–vapour phase change process inside porous media using modified enthalpy formulation



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ABSTRACT

In the present article, after critically analysing the drawbacks of the existing h -formulation based on Two Phase Mixture Model (TPMM), a modified formulation has been developed that can easily accommodate substantial density variations in the single phase regions. The results for steady one-dimensional complete liquid–vapour phase change problems of water inside a porous evaporator, obtained from the modified h - and the existing H -formulations, have been compared and excellent agreements have been observed for all tested cases. It has been also observed that the modified h -formulation requires significantly less computation time, although all variants of TPMM requires smoothing of effective diffusion coefficient in order to avoid “jumps” in the predicted properties. Since the proposed formulation does not require the definition of any artificial variable and in view of the identified advantages, the method is strongly recommended for the future use. Nevertheless, it should now be extended in order to accommodate the local thermal non-equilibrium condition and multi-dimensional phase change problems in presence of substantial density variations in the single phase regions.

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1. Introduction

Liquid–vapour phase change processes inside porous media are encountered in diversified scientific and engineering applications [1–3]. Numerical simulations of such problems essentially rely upon the traditional Separate Flow Model (SFM) [4,5], where the liquid and the vapour phases are considered as two distinct fluids with different properties, that generally assume different velocities, satisfying separate sets of conservation equations. In this respect, the complete phase change process within porous media could be characterised by the presence of three distinct regions: sub-cooled, two-phase mixture and superheated vapour regions. Since SFM is most often extremely complex and perhaps inconvenient for the direct use in numerical simulations, based on such classification, Ramesh and Torrance [6–8] proposed the Separate Phase Model (SPM) in order to solve problems involving boiling and natural

convection inside a fluid-saturated porous medium for each of these regions while continuously tracking the interface between them using a moving boundary approach. For practical applications, however, SPM still remains inconvenient for numerical implementation owing to the requirement of interface tracking and the presence of large number of coupled nonlinear equations.

Recognising the complexities and the inherent problems of SFM, Wang and Beckermann [9] proposed an enthalpy-based Two-Phase Mixture Model (TPMM) where the different phases are viewed as the constituents of a binary mixture. As explained later in section 2, Wang et al. [10] first identified that the original enthalpy (h -) formulation [9] is also not readily suitable for numerical implementation owing to several reasons. Therefore, they proposed the first modification to the original model and presented a study on boiling and natural convection in a porous layer heated from below. Later, Peterson and Chang [11] employed this modification [10], along with the assumption of Local Thermal Non-Equilibrium (LTNE) condition in order to investigate the phase change process from the sub-cooled liquid state to the saturated mixture inside a highly conductive porous channel.

However, a closer look into the first modification of TPMM [10], reveals that since some of the mixture variables and properties

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Nomenclature			
A_c	cross-sectional area of the pipe per unit radian = $R^2/2$, m^2	t	time, s
a_{l2}, a_{v2}	second order coefficients for liquid and vapour densities, respectively	T	temperature, K
\mathbf{b}	body force vector per unit mass, m/s^2	\mathbf{u}	velocity vector, m/s
$\hat{\mathbf{b}}$	normalised body force vector per unit mass = \mathbf{b}/g	u_g	gravitational velocity = \sqrt{gR} , m/s
C_p	specific heat at constant pressure, J/kgK	x	axial coordinates, m
D	capillary diffusion coefficient for enthalpy, kg/ms	<i>Greek symbols</i>	
f	hindrance function	α	thermal diffusivity = $k/\rho C_p$, m^2/s
Fr	Froude number = $u_{in}/u_g = u_{in}/\sqrt{gR}$	β	isobaric expansion coefficient, K^{-1}
g	acceleration due to gravity, m/s^2	ΔT	temperature difference over which T_{hi} is relaxed in the single-phase regions, K
h	specific enthalpy, J/kg	$\Delta\rho$	density difference between phases = $(\rho_l - \rho_v)$, kg/m^3
h_{co}	convective heat transfer coefficient at the outer surface of the pipe, W/m^2K	γ	advection correction coefficient
h_{fg}	latent heat of vaporization = $h_{v,sat} - h_{l,sat}$, J/kg	Γ	diffusion coefficient for enthalpy, $kg/m\ s$ (for h) or m^2/s (for H)
H	modified volumetric enthalpy = $\rho(h - 2h_{v,sat})$, J/m^3	ε	porosity of the medium
\mathbf{j}	diffusive mass flux vector, kg/m^2s	λ	relative mobility
J	capillary pressure function	μ	dynamic viscosity, kg/ms
k	thermal conductivity, W/mK	ν	kinematic viscosity, m^2/s
k_{rl}, k_{rv}	relative permeabilities for liquid and vapour, respectively	ρ	density, kg/m^3
K	permeability of porous media, m^2	σ	surface tension coefficient, N/m
l	length of individual segments, m	$\bar{\sigma}$	normalised surface tension coefficient, $\rho_l R_o \sigma / \mu_l^2$
L	length of the porous pipe, m	Ω	equivalent heat capacity
n	exponent of saturation in the expressions for relative permeabilities	<i>Subscripts</i>	
Nu_o	Nusselt number based on liquid properties = $h_{co}(2R)/k_l$	<i>eff</i>	effective
p	effective pressure, Pa	<i>h,H</i>	pertaining to <i>hand H</i> , respectively
P	perimeter of the pipe per unit radian = R , m	<i>in</i>	inlet
Pe	Peclet number = $u_{in}R/\alpha = RePr$	<i>k</i>	kinetic
Pr	Prandtl number = ν/α	<i>l</i>	liquid
\dot{q}''	constant heat flux, W/m^2	<i>i, e, h</i>	inlet, exit and heated, respectively
Q^*	normalised heat flux, = $\dot{q}'' R / \mu h_{fg}$	<i>s</i>	solid
R	pipe radius, m	<i>sat</i>	saturation
Re	Reynolds number = $u_{in}R/\nu$	<i>x</i>	pertaining to axial directions
Re_g	gravitational Reynolds number = $u_g R / \nu_l$	<i>v</i>	vapour
s	liquid saturation	<i>w</i>	wall
		<i>Superscripts</i>	
		*	dimensionless

remain undefined for the superheated vapour phase, it cannot be employed for the prediction of complete phase change process.¹ In order to eliminate this drawback, Wang [12] proposed the second modification of TPMM [9], by introducing the modified volumetric enthalpy $H = \rho(h - 2h_{v,sat})$ as the dependent variable for the energy conservation equation.² Nevertheless, all versions of TPMM are characterised by the coexistence of a two-phase zone, separated by the irregular as well as moving interfaces (for transient problems) of single-phase (either liquid or vapour) regions. Since these variants are obtained for fixed numerical grid, unlike SFM (or, SPM), there is no requirement for the complex as well as time consuming interface tracking. Possibly owing to the generality and the ease of numerical implementation, the H -formulation [12] is by far the most widely used method for the simulation of phase change process inside porous media [13–20]. Although this formulation [12] is applicable only under the assumption of Local Thermal Equilibrium (LTE) condition, it has been extended further in order

to accommodate the more general Local Thermal Non-Equilibrium (LTNE) condition [11,21,22].³

An additional problem that is encountered while simulating the complete liquid–vapour phase change process inside porous media is the occurrence of rapid, non-physical change in the predicted properties (e.g., temperature) over an extremely short distance⁴ that results primarily due to the presence of discontinuities in the effective diffusion coefficient across the interfaces between the single and the two phase regions. Recognising this difficulty, different researchers addressed this issue either by modifying the manner in which the cell face diffusivities are interpolated from their adjacent nodal values [18] or by assuming the saturation enthalpies ($h_{l,sat}$, $h_{v,sat}$) and hence the latent heat (h_{fg}) to be functions of the saturation pressure [23–26]. Although

³ For LTNE condition, the solid matrix and the fluid medium can locally coexist at different temperatures and the respective energy conservation equations are coupled to each other through the volumetric heat exchange term.

⁴ Henceforth shall be referred to as the “jump”, which has no relation to the physical mass and heat “jump” conditions across the liquid–vapour interfaces, used in Volume of Fluid (VOF)-like methods.

¹ Where phase change takes place from the sub-cooled liquid phase to the superheated vapour phase.

² Henceforth shall be referred to as the H -formulation.

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