View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by FAMENA Repository

On Mixture Model Application in Numerical Modeling of Boiling Phenomena

Alen Cukrov[1], Željko Tuković[2], Bojan Ničeno[3], Ivanka Boras[1], Antun Galović[1]

[1] Department of Thermal and Process Engineering,
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia

[2] Department of Energy, Power Engineering and Environment,
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia

[3] Nuclear Energy and Safety,
Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

acukrov@fsb.hr

ABSTRACT

In this paper, a description of the multiphase modeling approach known as mixture model, or drift-flux model, is given. The mixture model is based on conservation equations for mass, momentum and energy of a mixture of all phases present in the flow. The individual phases are assumed to be in equilibrium over small distances of space, computational cells in practical terms. In order to account for different velocities each phase in reality has, the drift velocity of the dispersed phase is introduced and solved with algebraic set of equations based on empirical data. The mixture model described in this work will be used for boiling simulations, with quenching as the final application. Therefore, the fluids of interest are water and vapour, and the model should be capable to cover a range of boiling regimes. The results of a literature survey will be used to assess the relative advantages and shortcomings of the mixture model for simulations of boiling during quenching. The steps regarding future work are given.

KEY WORDS

Multiphase flow modeling, Heat transfer, Phase change.

1. INTRODUCTION

The boiling phenomenon is of great interest in engineering practice, especially in the area of cooling due to high amount of heat which could be removed by such process. This phenomenon is followed with the complex mathematical models that, among others, require significant computational resources and time. However, for application of a certain computational method

in practice, an emphasis is put on the accuracy of the computational method together with reasonable time consumption. To accomplish this, the *mixture model* comes in handy.

The aim of this paper is to provide a conceptual basis for the development of a numerical solver capable to predict the temperature field in a solid during the immersion quenching process. The paper is organised as follows. In Section 2, the governing equations for mixture continuity, momentum and energy together with the continuity equation for dispersed phase are presented as well as the constitutive relations and the expressions for the mixture properties. A concise overview on the approaches for modeling the boiling phenomena applied by researchers who employ the mixture model is given in Section 3. At the end, in Section 4 the conclusions are drawn and the recommendations regarding future work are given.

2. MATHEMATICAL MODEL

2.1 Mixture General Balance Equation

The mathematical model that governs this multiphase flow problem is formulated using the general balance equation that describes the transport phenomena in each phase, in conjunction with the interfacial balance equation which takes into account the phenomena occurring at the interface between the phases. After performing an Eulerian time averaging on this equation set and introduction of mixture variables, one obtains the mixture general balance equation, which reads [1]

$$\frac{\partial \rho_m \psi_m}{\partial t} + \nabla \cdot \left(\rho_m \psi_m \mathbf{v}_m \right) = -\nabla \cdot \mathbb{J}_m + \rho_m \phi_m + I_m \tag{1}$$

where the subscript *m* denotes the mixture of phases. The last term on the right hand side of the above equation includes the interfacial transport phenomena and thus distinguishes this equation from the single-phase flow general transport equation. The complete derivation of Eq. (1) one can found in the book of Hibiki and Ishii [1]. A more insight into the terms of Eq. (1) is given in the remainder of the Section.

2.2 Mixture Properties

The physical quantities that appear in Eq. (1) are obtained by weighting a particular quantity by a *local time fraction* α of each phase [1]. The relationship between the local time fractions for a two phase system is

$$\alpha_1 + \alpha_2 = 1 \tag{2}$$

where the subscript 1 denotes the continuous phase and 2 denotes the dispersed phase.

Hence, the mixture density reads [1]

$$\rho_m = \sum_{k=1}^{2} \alpha_k \overline{\overline{\rho_k}} \tag{3}$$

The mixture pressure is then [1]

$$p_m = \sum_{k=1}^{2} \alpha_k \overline{\overline{p_k}} \tag{4}$$

The velocity is expressed in terms of the mixture center of mass velocity [1]

$$\mathbf{v}_m = \frac{\sum_{k=1}^{2} \alpha_k \overline{\overline{\rho_k}} \mathbf{v}_k}{\rho_m} \tag{5}$$

The mixture enthalpy* is expressed in the same fashion [1]

$$h_m = \frac{\sum_{k=1}^{2} \alpha_k \overline{\overline{\rho_k}} h_k}{\rho_m} \tag{6}$$

2.3 Mixture Model Field Equations

The mixture general balance equation, Eq. (1), serves as a base in derivation of the mixture model field equations. By setting the general physical quantity ψ_m to appropriate extensive property as well as including the relevant surface fluxes $\mathbb{J}_m$ and source terms ϕ_m, one obtains the mass, momentum and energy conservation equations for a mixture [1]:

The mixture continuity equation

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot \left(\rho_m \mathbf{v}_m \right) = 0 \tag{7}$$

The mixture momentum equation

$$\frac{\partial \rho_m \mathbf{v}_m}{\partial t} + \nabla \cdot \left(\rho_m \mathbf{v}_m \mathbf{v}_m \right) = -\nabla p_m + \nabla \cdot \left[\bar{\boldsymbol{\sigma}} + \boldsymbol{\sigma}^T - \sum_{k=1}^{2} \alpha_k \overline{\overline{\rho_k}} \mathbf{V}_{km} \mathbf{V}_{km} \right] + \rho_m \mathbf{g}_m + \mathbf{M}_m \tag{8}$$

The mixture thermal energy equation

$$\begin{aligned} &\frac{\partial \rho_m h_m}{\partial t} + \nabla \cdot \left(\rho_m h_m \mathbf{v}_m \right) = -\nabla \cdot \left(\bar{\mathbf{q}} + \mathbf{q}^T \right) + \sum_{k=1}^{2} \alpha_k \mathbf{V}_{km} \cdot \nabla \overline{\overline{p_k}} \\ &-\nabla \cdot \left(\sum_{k=1}^{2} \alpha_k \overline{\overline{\rho_k}} h_k \mathbf{V}_{km} \right) + \frac{Dp_m}{Dt} + \Phi_m^{\mu} + \Phi_m^{\sigma} + \Phi_m^{i} \end{aligned} \tag{9}$$

The complete set of field equations is obtained by introduction of *the continuity equation for dispersed phase*, which reads [1]

$$\frac{\partial \alpha_2 \overline{\overline{\rho_2}}}{\partial t} + \nabla \cdot \left(\alpha_2 \overline{\overline{\rho_2}} \mathbf{v}_m \right) = \Gamma_2 - \nabla \cdot \left(\alpha_2 \overline{\overline{\rho_2}} \mathbf{V}_{2m} \right) \tag{10}$$

* In Eq (6) and Eq. (9), the authors in [1] denote the enthalpy as *i*.

where the source term Γ_2 denotes the vapour generation rate. The mathematical model is completed by a set of constitutive equations, among them the kinematic constitutive equation, which plays important role in handling the momentum transfer within this model.

2.4 Kinematic Constitutive Equation

The approximation of the two phases as one continuum, i.e. a mixture, leads to a formulation of one momentum equation for the mixture of phases. Thus vanishes the significant information about the momentum transfer in the flow. Therefore, a kinematic constitutive equation is included in the mathematical model to consider the different velocities that each phase in reality has. To this end, a diffusion velocity is defined as [1]

$$\mathbf{V}_{km} = \mathbf{v}_k - \mathbf{v}_m \tag{11}$$

where $\mathbf{v}_k$ is the velocity of the phase *k*. The diffusion velocity is related to drift velocity which describes the relative motion of the dispersed phase. This relationship reads [1]

$$\mathbf{V}_{2m} = \frac{\overline{\overline{\rho_1}}}{\rho_m}\mathbf{V}_{2j} = -\frac{\alpha_1\overline{\overline{\rho_1}}}{\alpha_2\rho_m}\mathbf{V}_{1j} \tag{12}$$

where $\mathbf{V}_{1j}$ and $\mathbf{V}_{2j}$ denote the drift velocities of phase 1 and phase 2 respectively. The drift velocities are defined by the empirical correlations.

3. LITERATURE REVIEW

Due to its relative simplicity and effectiveness, the mixture model is suitable for applications in industry. This section gives a brief review on the work of researchers who employ the mixture model to solve real engineering problems where the boiling is present. In these reviews, an emphasis is put on the approaches used to model the boiling phenomena.

Krause, Schüttenberg and Fritsching [2] develop a numerical model for simulation of quench cooling process. The developed model is implemented in the commercial CFD code Fluent 6.3. In order to model the boiling phenomena, the mixture model is used in conjunction with the bubble crowding model. The latter models the boiling by making an assumption that the spherical bubbles of constant diameter are present in the computational domain and that their population depends on the actual boiling regime present in the flow. This means, if the film boiling is the actual regime, then a huge population of the bubbles will appear in the vicinity of the heated surface instead of continuous vapour film. The authors state that the bubble crowding approach has almost the same effect on heat transfer mechanisms during film boiling as the approach with the continuous vapour film. The phase change mode is determined by the fluid temperature with respect to the saturation temperature. The defined mass exchange source term utilize the mass transfer coefficient which takes into account whether is the condensation or boiling present in the flow, depending on the temperature of the vapour-liquid mixture. This coefficient captures the complete boiling curve by inspection of the mixture temperature with respect to the predefined Leidenfrost and critical heat flux (CHF) temperatures together with the saturation temperature. The obtained results agree well with the measurement data.

Lobón, *et al*. [3,4] model the direct steam generation in parabolic-through solar collector by using the mixture model formulation implemented in the commercial CFD package STAR-CCM+. The authors performed the steady state [3] and the transient [4] numerical simulations. In order to model the boiling phenomena, the authors use a semi-empirical approach. Therefore, the vapour mass generation on the heated surface is considered to be proportional to the surface boiling heat flux which is computed using the Rohsenow correlation given in [5]. Also, the applied model considers the boiling and condensation that occur in the bulk fluid. This is achieved by the mass transfer relation which is used to determine whether the condensation or boiling is to be modelled, depending on the sign of the difference between actual temperature of the fluid mixture and saturation temperature. The obtained results have shown the reliability of the applied method.

Kopun *et al*. [6] model the film and transition boiling regime during the immersion quenching process using Euler-Euler method (the *two-fluid* model) implemented in the CFD code AVL-FIRE. In the two-fluid model, the behaviour of each phase is described by its own set of conservation equations. These equations sets are coupled via the additional terms which account for the interfacial transfer. Although Kopun *et al*. employ the two fluid model, they formulate the energy equation for a mixture. Their model is an extension of the model previously developed by Srinivasan *et al*. [7]. By utilization of the mixture energy equation instead of two separate energy equations, the existence of the uncertainties in interfacial heat transfer modeling is eliminated [7]. The applied boiling model is based on the assumption that the phase change rate is proportional to heat transfer rate. This assumption is realized within the governing equations by inclusion of the mass exchange term whose value is proportional to the boiling heat transfer coefficient. The boiling heat transfer coefficient depends on the actual boiling regime which is present in the flow. The extension of the base model, which is developed in [7], is done by the authors by taking into account additional forces (wall lubrication force and lift force) in the momentum exchange term as well as taking into consideration the variable Leidenfrost temperature during the quench cooling process. The authors developed a procedure for computation of Leidenfrost temperature which involves the sub-cooled temperature and is based on blended correlations of Cheng [8] and Drucker [9]. The applied extensions of the base model resulted in improvement of the, already reliable, results obtained previously.

4. CONCLUSION AND PERSPECTIVES

The adequate numerical modeling of boiling phenomena plays the key role in numerical simulation of quench cooling process. Among the available multiphase flow modeling methods, the mixture model is chosen as a base for development of a numerical solver capable to successfully predict the temperature evolution in a solid during the immersion quenching process. This paper has briefly presented the model fundamentals and the findings reported by the researchers who successfully employ the model in solving real engineering problems. The main advantages of the mixture model are the low time consumption and its simplicity in comparison to other multiphase flow models. However, since the mixture model is not capable to take into account the large scale interfaces, its application is followed with an assumption that the quenched part is immersed in a quenchant liquid.

In future work, the aim is to develop a numerical solver able to model the boiling phenomena. The developed method is intended to be implemented within the framework of OpenFOAM, a C++ library for Computational Continuum Mechanics. Since the quenching process belongs to conjugate heat transfer problems, the great OpenFOAM capabilities in handling fluid structure interactions would be beneficial. This includes dynamic mesh handling [10], which could be

employed to model the immersion process together with the heat transfer phenomena present in both, the fluid and the solid domain.

NOMENCLATURE

$\mathbf{g}$	gravity field
h_k	local mean enthalpy
h_m	mixture enthalpy
I_m	interfacial source term for mixture balance equations
$\mathbb{J}$	flux
$\mathbf{M}_m$	momentum source for mixture
$\overline{\overline{p_k}}$	bulk mean pressure
p_m	mixture pressure
$\mathbf{q}$	heat flux
$\overline{\mathbf{q}}$	mixture conduction heat flux
$\mathbf{q}^T$	mixture turbulent heat flux
$\mathbf{V}_{kj}$	drift velocity
$\mathbf{V}_{km}$	diffusion velocity
$\mathbf{v}_k$	weighted mean velocity at bulk phase
$\mathbf{v}_m$	mixture center of mass velocity

Greek symbols

α_k	void fraction of phase *k*
Γ_2	mass generation for the dispersed phase (vapour)
$\overline{\overline{\rho_k}}$	mean density
ρ_m	mixture density
$\boldsymbol{\sigma}$	mixture viscous stress tensor
$\boldsymbol{\sigma}^T$	mixture turbulent stress tensor
Φ_m^i	interfacial mechanical energy transfer term
Φ_m^μ	mixture viscous dissipation term
Φ_m^σ	surface tension effect term
ϕ	source term
ψ	extensive property

REFERENCES

1. Ishii, M. and Hibiki, T., *Thermo-Fluid Dynamics of Two-Phase Flow*, Springer, New York, 2011.
2. Krause, F., Schüttenberg, S. and Fritsching, U., Modelling and simulation of flow boiling heat transfer, *International Journal of Numerical Methods for Heat and Fluid Flow*, Vol. 20, No. 3, pp 312-331, 2010.

3. Lobón, D.H., Baglietto, E., Valenzuela, L., and Zarza, E., Modeling direct steam generation in solar collectors with multiphase CFD, *Applied Energy*, Vol. 113, pp 1338-1348, 2014.
4. Lobón, D.H., Valenzuela, L., and Baglietto, E., Modeling the dynamics of the multiphase fluid in the parabolic-trough solar steam generating systems, *Energy Conversion and Management*, Vol. 78, No. 0, pp 393-404, 2014.
5. Rohsenow, W.M., A method of correlation heat transfer data for surface boiling of liquid, *Transactions of ASME*, Vol. 74, pp 969-976, 1952.
6. Kopun, R., Škerget, L., Hriberšek, M., Zhang, D.S., Stauder, B., and Greif, D., Numerical simulation of immersion quenching process for cast aluminium part at different pool temperatures, *Applied Thermal Engineering*, Vol. 65, No. 1-2, pp 74-84, 2014.
7. Srinivasan, V., Moon, K.M., Greif, D., Wang, D.M., and Kim, H.M., Numerical simulation of immersion quench cooling process using an Eulerian multi-fluid approach, *Applied Thermal Engineering*, Vol. 30, No. 5, pp 499-509, 2010.
8. Cheng, S.C., Lau, P.W.K., and Poon, K.T., Measurements of true quench temperature of subcooled water under forced convective conditions, *Int. J. Heat Mass Transfer*, Vol. 28, No. 1, pp 235-243, 1985.
9. Drucker, M., Dhir, V.K., Effects of High Temperature and Flow Blockage on the Reflood Behavior of a 4-rod Bundle, EPRI Report, p 2122, 1981.
10. Jasak, H. and Tuković, Ž., Automatic mesh motion for the unstructured finite volume method, *Transactions of FAMENA*, Vol. 30, No. 2, pp 1-18, 2007.