International Journal of Multiphase Flow 69 (2015) 115–127

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Modeling of two-phase flow in porous media with heat generation

M. Taherzadeh [a], M.S. Saidi [b,*]

[a] Department of Energy Engineering, Sharif University of Technology, P.O. Box 11365-11155, Tehran, Iran
[b] Department of Mechanical Engineering, Sharif University of Technology, P.O. Box 11365-11155, Tehran, Iran

ARTICLE INFO

Article history:
Received 13 July 2014
Received in revised form 21 September 2014
Accepted 22 October 2014
Available online 20 November 2014

Keywords:
Two-phase flow
Debris bed
Dryout
Interfacial area
Friction force

ABSTRACT

The main purpose of this work is investigation of coolability of a boiling debris bed. The main governing equations are derived using volume averaging technique. From this technique some specific interfacial areas between phases are appeared and proper relations for modeling these areas are proposed. Using these specific areas, a modification for the Tung/Dhir model in the annular flow regime is proposed. The proposed modification is validated and the agreements with experimental data are good. Finally, governing equations and relations are implemented in the THERMOUS program to model two-phase flow in the debris bed in the axisymmetric cylindrical coordinate. Two typical configurations including flat and mounted beds are considered and the main physical phenomena during boiling of water in the debris bed are studied. Comparing the results with the one-dimensional analysis shows higher specific power of the bed.

Introduction

Porous media and the corresponding heat transfer phenomena has been attracted considerable attention due to its relevance to a wide variety of application area in engineering and science such as underground heat exchangers for energy saving, oil extraction, solar collectors, nuclear reactors, cooling electronic devices, thermal insulations, geothermal energy, etc. These applications are discussed and reviewed by Nield and Bejan (2006), Ingham and Pop (1998, 2005, 2001), Vafai (2005) and Ingham et al. Bejan et al. (2004).

Regarding the safety of a nuclear power plant such processes with two-phase flow in porous media are at least in discussion since the severe accident in the nuclear power plant TMI-II in Harrisburg (USA) on March 28, 1979. During a very unlikely severe accident, all normal and emergency cooling systems can be failed and thus due to high residual nuclear heat power of the core, water is evaporated and the core temperature is increased until fuel rods and other structures in the core start to melt. This melt can flow through lower parts of the core and create a jet of molten material, that is falling into lower head of pressure vessel where water exists. Because of interaction of molten material with water in the lower head, fragmentation can occur and a porous media that is called "debris bed" is created. This was observed in many experimental facilities, and the average debris size is of the order of a few millimeters (Magallon, 1997). To avoid environmental pollution with radioactive material, re-melting and further destruction, especially the failure of safety barriers, cooling of this porous media with internal heat sources is important. Due to non-availability of forced coolant flow by pumping, this heat can only be removed by evaporation of cooling water. For long term cooling of the configuration, all evaporated water has to be replaced by water inflow due to natural forces. At the same time, the produced steam must escape the porous structure driven by buoyancy forces.

Several experimental and theoretical programs on debris coolability have been performed, especially at the beginning of 1980s. Indeed a non-coolable debris bed is assumed to quickly rise in temperature, due to the residual decay heat, melt and form a large molten pool that would expand even when surrounded by water, and threaten the integrity of the vessel. In most of these experimental and theoretical studies, one-dimensional debris beds were considered (Lipinski, 1984). Recently, two-dimensional effects have been studied in more details, either experimentally (Décossin, 2000; Berthoud and Valette, 1994) or numerically (Buck et al., 1998; Béchaud et al., 2001). It appears that the counter-current flow limitation, which is always present in one-dimensional situations, can be avoided in some two-dimensional configurations, leading to a higher critical heat flux. Some authors used pressure loss measurements in isothermal air/water flow experiments to investigate the drag forces in the particle bed between particle and fluid phases as well as two fluid phases (Chu et al., 1983a; Chen et al., 1984) for both counter and co-current flow of fluid phases. In addition, it has been observed

* Corresponding author. Tel.: +98 2166165558.
E-mail address: mssaidi@sharif.edu (M.S. Saidi).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.10.013
0301-9322/

that local thermal equilibrium may not exist everywhere in the debris bed, even for heated debris covered by water at saturation temperature (Atkhen and Berthoud, 2003). The existence of temperature differences between the solid particles, the water and the steam makes modeling and experimental measurements more difficult. Furthermore, flow patterns are complex since, for very high temperature particles, steam becomes the "wetting" phase due to the presence of a stable steam film around the particles. This was observed experimentally on single spheres. A theoretical model for heat transfer around spheres was proposed under film-boiling regime (Dhir and Purohit, 1978). However, the results obtained for spheres are difficult to apply to particle debris beds. Because of the lack of experimental data on real debris beds, models must rely on several assumptions. Also, several other experiments have been performed to investigate particle size distribution and porosity of debris bed (Hohmann et al., 1998; Annunziato et al., 1994).

The present work begins with deriving the governing equations to study the two phase flow in the debris bed and then is focused on interfacial areas and friction force between fluid phases. Finally, using THERMOUS program the coolability of two typical debris bed configurations is studied. THERMOUS code is an in-house developing software for thermal–hydraulic modeling of multi-phase flow which is validated successfully for single phase flow in porous media previously (Saidi and Taherzadeh, 2013, 2014) and in the present work is applied for numerical calculations of two phase flow in porous media.

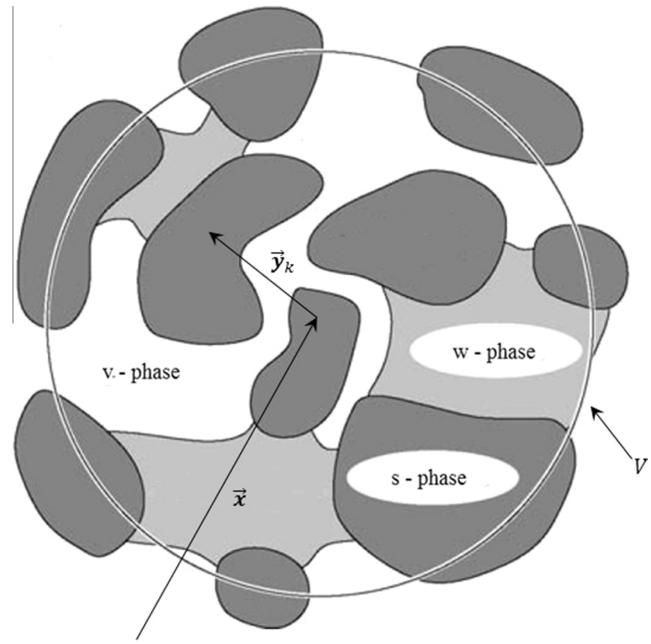

Fig. 1. Position vectors and averaging volume.

Governing equations

Governing equations for modeling the two-phase flow in porous media can be obtained from volume averaging of point conservation equations (Espinosa-Paredes, 2010). For a Ψ property of k-phase, including vapor, water or solid phase, two averaging value including volumetric averaging (Eq. (1)) and intrinsic averaging (Eq. (2)) are defined and the relation between these two values is presented in Eq. (3).

$$\langle \Psi_k \rangle = \frac{1}{V}\int_{V_k} \Psi_k dV \tag{1}$$

$$^{i}\langle \Psi_k \rangle = \frac{1}{V_k}\int_{V_k} \Psi_k dV \tag{2}$$

$$\langle \Psi_k \rangle = \zeta_k^i \langle \Psi_k \rangle; \quad \zeta_v = \varepsilon\alpha,\ \zeta_w = \varepsilon(1-\alpha),\ \zeta_s = (1-\varepsilon) \tag{3}$$

where V, V_k, ζ_k, ε and α are the averaging volume, volume of the k-phase, volume fraction of k-phase, porosity and void fraction respectively. Position vectors and averaging volume is indicated in Fig. 1. Also subscripts v, w and s refer to vapor, water and solid phases respectively.

The general form of point conservation equation for Ψ property in the k-phase can be considered as:

$$\frac{\partial(\rho_k \Psi_k)}{\partial t} + \nabla\cdot(\rho_k \overrightarrow{\mathbf{U_k}} \Psi_k) + \nabla\cdot(\overrightarrow{\mathbf{D_k}}) = \rho_k f \tag{4}$$

Eq. (4) represents the conservation of quantity Ψ_k and from Table 1 depending on the choice of the quantity can be used for mass, momentum and energy conservation equation for each phase.

In Table 1, $\overrightarrow{\mathbf{U}_k}$, P_k, $\overrightarrow{\tau_k}$, $\overrightarrow{\mathbf{g}_k}$, e_k, ρ_k, $\overrightarrow{\mathbf{q}_k''}$ and q_k''' are velocity, pressure, tension, acceleration, internal energy, density, heat flux and volumetric heat source for each phase respectively.

When the local instantaneous transport equations are averaged over the volume, terms arise which are averages of derivatives. In order to interchange differentiation and integration in the averaging transport equations, two special averaging theorems are needed (Whitaker, 1999), one for time domain and another for space domain:

Table 1
Parameters for point conservation equation.

	Ψ_k	$\overrightarrow{\mathbf{D_k}}$	f
Mass	1	0	0
Momentum	$\overrightarrow{\mathbf{U_k}}$	$p_k\overrightarrow{\mathbf{I_k}} - \overrightarrow{\tau_\mathbf{k}}$	$\overrightarrow{\mathbf{g_k}}$
Energy	$e_k - \frac{p_k}{\rho_k}$	$\overrightarrow{\mathbf{q_k''}} - (p_k\overrightarrow{\mathbf{I_k}} - \overrightarrow{\tau_\mathbf{k}}).\overrightarrow{\mathbf{U_k}}$	$\overrightarrow{\mathbf{g_k}}.\overrightarrow{\mathbf{U_k}} + \frac{q_k'''}{\rho_k}$

$$\left\langle \frac{\partial \Psi_k}{\partial t} \right\rangle\Bigg|_x = \frac{\partial \langle \Psi_k \rangle}{\partial t}\Bigg|_x - \frac{1}{V}\int_{A_k} \Psi_k|_{x+y_k} \overrightarrow{\mathbf{U_k}} \cdot n_k dA \tag{5}$$

$$\langle \nabla \Psi_k \rangle|_x = \nabla \langle \Psi_k \rangle|_x + \frac{1}{V}\int_{A_k} \Psi_k|_{x+y_k} n_k dA \tag{6}$$

In Eqs. (5) and (6), $\overrightarrow{y_k}$ represent the position vector relative to the centroid of the averaging volume as indicated in Fig. 1. The property Ψ can be decomposed into two parts including volume-averaged quantity $\langle \Psi \rangle$ and spatial deviation quantity $\dot{\Psi}$ Gray, 1975:

$$\Psi_k = {}^{i}\langle \Psi_k \rangle + \dot{\Psi}_k \tag{7}$$

However, it is shown that for all practical problems in porous media, the spatial deviation quantity is small compared to the volume-averaged quantity (Whitaker, 1999) and thus in the present work is ignored. Using Eqs. (1)–(7), the volume averaged general point conservation equation can be expressed as:

$$\frac{\partial(\zeta_k \rho_k \Psi_k)}{\partial t} + \nabla\cdot(\zeta_k \rho_k \overrightarrow{\mathbf{U_k}} \Psi_k) + \nabla\cdot(\zeta_k \overrightarrow{\mathbf{D_k}}) = \zeta_k \rho_k f + \tag{8}$$

$$\frac{1}{V}\int_{A_k} \rho_k \Psi_k|_{x+y_k} \overrightarrow{\mathbf{U_k}} \cdot n_k dA - \frac{1}{V}\int_{A_k} \rho_k \overrightarrow{\mathbf{U_k}} \Psi_k|_{x+y_k} n_k dA - \frac{1}{V}\int_{A_k} \overrightarrow{\mathbf{D_k}}\Big|_{x+y_k} n_k dA$$

In Eq. (8), the integral terms represent exchange between phases through their interfaces. For continuity equations of water and vapor phases, these terms represent mass transfer or in another word phase change rate. For momentum equations of water and vapor phases, these terms represent momentum interchange between phases for example due to friction forces or mass transfer (Espinosa-Paredes, 2001). For energy equations of water, vapor and solid phases, these terms represent heat transfer between phases