Prediction of dryout and post-dryout heat transfer using a two-phase CFD model

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A B S T R A C T

This study focuses on development of an integrated CFD model for diabatic high quality two-phase flow including trans-dryout regions from annular-mist regime to mist regime. One unified three-field CFD model accounting for droplets, gas, and liquid film was developed to simulate both pre and post dryout regions, with local models to determine the dryout occurrence. The thin liquid film model was coupled to the gas core flow model, which is described using the Eulerian–Eulerian approach. For the post-dryout region, the various heat and mass transfer mechanisms between the wall, the gas phase, and the droplets were identified, including the wall-gas convective heat transfer, the droplet evaporation, the droplet-wall direct contact heat transfer and the thermal radiation, to calculate the temperature of the wall and the fluid. Of the most interests, dryout location and wall temperature measurements from a post-dryout heat transfer experiment have been used for the validation. Simulation results show that the dramatic temperature excursion could be well captured using current models. Nevertheless, more work will be continued to improve the accuracy of the results.

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1. Introduction

Two-phase fluid boiling flow is extremely efficient for cooling of high heat flux systems, e.g., heat exchangers, nuclear reactors and modern electronic devices. Among them, annular-mist two-phase fluid flow regime plays an important role in many applications. This type of flow regime can be encountered in a wide range of pressures, mass flow rates and flow qualities. In annular-mist flow, the liquid phase flows partly as a thin liquid film on the channel wall and partly as entrained droplets in the gas core.

In the annular-mist flow with heated walls, the liquid film is depleted by both the entrainment of liquid droplets and by the evaporation. When the liquid film experiences almost complete depletion and no longer covers the wall, the heat transfer between the fluid and the channel wall deteriorates, leading to the onset of boiling crisis called dryout. As the flow develops further downstream in the post-dryout region, the liquid flows only as droplets in the mist flow regime, and the channel wall temperature increases to a higher level. The dryout occurrence and the downstream post-dryout wall temperature excursion could damage the channel wall. As a result, accurate prediction of the dryout occurrence and the post-dryout heat transfer are crucial to the optimized design and operation of heat systems.

Due to the complexity of the governing phenomena, the dryout occurrence is still predominantly evaluated by employing empirical correlations, which are based on expensive experiments and apparently are limited to the specific range of geometries and operational conditions [1]. The extrapolation of these correlations to systems and conditions much outside the range for which they were developed may be not valid. To resolve theses limitations, several phenomenological and mechanistic approaches have been proposed to predict the liquid film propagation, which can then be used to indicate the dryout occurrence when the liquid film thickness or flow rate decreases to almost zero.

The phenomenological modeling of annular-mist flow was proposed to calculate the liquid film flow based on the rates of evaporation, and droplet deposition and entrainment [2,3]. In these types of approaches, the dryout is assumed to occur when the liquid film flow rate or corresponding film thickness decreases to zero or below a critical value [4–6]. Furthermore, some system and sub-channel codes, e.g., CATHARE-3 [7,8], COBRA-TF [9], VIPRE-W [10], MONA-3 [11] and FIDAS [12,13], have taken advantage of the one-dimensional phenomenological models for dryout prediction, to include the three-field calculation module of the gas, the liquid film and the droplets. However, they still cannot solve the general problem for complex geometries, e.g., the flow channels with obstacles.

On the other hand, mechanistic approaches employing the computational fluid dynamics (CFD) method have been developed to
simulate the two-phase flow, including the annular-mist flow [14,15]. Since the liquid film is very thin near the dryout location, it is prohibitively expensive to directly resolve the liquid film [16]. Various approximations have been developed instead. A lumped parameter model of liquid film was first included in a two-fluid CFD model for nuclear fuel bundle applications by Anglart et al. [17]. Bai and Gosman [18] proposed a two-dimensional liquid film model, which can be coupled with the gas core flow for annular-mist flow simulation [19]. Based on the thin liquid film modeling, the annular-mist flow development with liquid film depletion could be captured [20].

The phenomenological models usually assume that the liquid film completely disappears when dryout occurs. Experimental evidences, however, showed that dryout may occur even when the liquid film flow rate is still high [5,21]. Thus, it seems plausible to argue that dryout occurs when the liquid film flow rate or thickness decreases to a minimum or critical value. The minimum stable film flow rate has been previously investigated using a total energy balance for the leading edge of the liquid film was developed, which shows potential for dryout predictions [5]. Furthermore, correlations based on the force balance theory were also developed for robust and convenient applications [6,22].

The mist flow encountered downstream of the dryout point is called post-dryout regime, where thermal non-equilibrium can be observed. Various heat exchange modes occur between the gas phase, the liquid droplets, and the channel wall. Usually the heat is transferred from the gas to the liquid droplets, where the droplets and the gas have different temperatures. Previously, predictions of the wall temperature and the heat transfer between the wall and fluid were typically one-dimensional correlations, based on the thermal equilibrium or the thermal non-equilibrium assumptions [23,24]. Even though some more heat transfer paths were considered including the convective, the thermal radiation, and the droplet-wall direct contact heat transfers, the detailed thermal non-equilibrium across the flow channel cannot be accounted for, which makes the accurate wall temperature prediction difficult. Although many correlations on post-dryout heat transfer were developed and improved, to account for various governing phenomena, large gap still exists between the calculation and the measurements, especially for some complex geometry applications [25,26].

In the current work, an integrated CFD model to include both the pre-dryout annular-mist flow and the post-dryout mist flow, with post-dryout heat transfer accounted for, has been developed. The three-field annular-mist CFD model couples the thin liquid film model with the two-field two-fluid model of the gas core flow including the gas phase and the droplets. The dryout occurrence was predicted using a critical film thickness model. The various post-dryout heat transfer mechanisms were identified and calculated to give the wall and the fluid temperatures.

2. Modeling of annular-mist flow

The current three-field annular-mist flow model is based on the coupling of the thin liquid film model and the Eulerian–Eulerian gas core flow model, with droplets dispersed in the gas phase.

2.1. Liquid film modeling

In diabatic annular-mist two-phase flow, e.g., a vertical channel as shown in Fig. 1, the liquid phase flows partly as a thin liquid film on the heated wall and partly as droplets in the gas core. The liquid
film, especially in the upstream of the dryout point, is sufficiently thin. As a result, we can assume that there is no film flow in the wall-normal direction, which implies that the advection can be treated in the wall tangential direction and diffusion in the wall normal direction, as shown in Fig. 2. As a result, the transport equations for the liquid film can be integrated in the wall normal direction, leading to the two-dimensional equations (only in the wall tangential direction).

All the liquid film properties, which vary across the film thickness, appear as depth-averaged quantities and are in general defined as

$$\bar{\varphi} = \frac{1}{\delta} \int_0^\delta \varphi \, dy$$  \hspace{0.5cm} (1)

where $\delta$ is the film thickness, $\varphi$ is any liquid film property variable, and $y$ is the coordinate for wall normal direction. For simplicity, the bar is omitted for all the depth-averaged liquid film properties used in the following description. The resulting mass, momentum, and energy equations are integrated in the wall normal direction as

$$\frac{\partial (\rho \delta)}{\partial t} + \nabla \cdot (\rho \delta U) = S_\delta$$  \hspace{0.5cm} (2)

$$\frac{\partial (\rho \delta U)}{\partial t} + \nabla \cdot (\rho \delta U U) = -\delta \nabla \cdot p + S_U$$  \hspace{0.5cm} (3)

$$\frac{\partial (\rho \delta h)}{\partial t} + \nabla \cdot (\rho \delta h U) = S_h$$  \hspace{0.5cm} (4)

where $U$ is the mean film velocity, $h$ is the mean film specific enthalpy, $\nabla$ is the nabl operator tangential to the surface, $\rho$ is the density, $p$ is the total pressure, and $S_\delta$, $S_U$ and $S_h$ are the source terms. It is noted that the advection for all the equations are explicitly described, however, the diffusion and the external sources are modeled as source terms. The liquid film has complex interaction with the gas core flow, which means that corresponding models should be included as source terms to consider all the phenomena of concern.

2.1.1. Mass source terms

Fig. 3(a) depicts the main mechanisms of mass transfer considered in the present model. As indicated, the sources and sinks of mass in the liquid film are mainly due to the phase change, as well as the droplet deposition and entrainment.

The phase change model considers evaporation of the liquid film, where some or all of the evaporating liquid is transferred into the gas core.

The droplet deposition is the direct mass source from the dispersed droplets. It is formulated as the deposition rate.

The film entrainment is mainly due to the disturbance waves, and the mechanisms has been experimentally and theoretically investigated, with close relation with liquid film-gas interfacial shear stress, boiling effect in the liquid film, and the surface tension [3,27]. Modeling of the entrainment rates will be discussed in the following section. A certain amount of liquid film will be transferred to the gas core as droplets. Once the properties of entrained droplets are known, e.g., the mass transfer rate and the droplet size, the formulation of the entrainment source term is similar to that of deposition.

When the droplets impinge the liquid film or the wall, they may undergo different behavior, e.g., they can stick, spread, rebound and splash [28]. For the overall effect, they can all be considered as droplet deposition and entrainment, and can be modeled with different restitution coefficients.

Other mass sources can also be included according to the specific phenomena, e.g., the curvature separation when the liquid film flows around a corner and the dripping when the film flows on the underside of inclined surfaces.

2.1.2. Momentum source terms

As shown in the integrated momentum equation, the source terms for the film momentum have been split into pressure-based part from the tangential gradients in wall normal forces and the stress-based part from the forces in the wall tangential direction.

As presented in Fig. 3(b), the pressure-based momentum sources include the local gas phase pressure, the hydrostatic pressure, capillary pressure, vapor recoil pressure, and the pressure from deposition and entrainment [20].

Fig. 3(c) shows the stress-based momentum sources, which consist of gravity force, shear stress, thermocapillary force, contact angle force, and the forces due to droplet deposition and entrainment [20].

2.1.3. Energy source terms

The energy sources include mainly such effects as wall heat transfer, interfacial heat transfer, and evaporation, as well as...
sources from droplet deposition and entrainment, and possibly radiation [20], as shown in Fig. 3(d).

In addition, other source terms can be included, e.g., radiation, if the effects are significant for the phenomena under consideration.

2.2. Modeling of gas core flow

In the Eulerian–Eulerian approach, both phases including the gas phase and the droplets are described using the Eulerian conservation equations based on the two-fluid model [29]. Both phases are treated as inter-penetrating continua, and are represented by averaged conservation equations.

The governing equations for the gas core flow are described as

\[
\frac{\partial a_k q_k}{\partial t} + \nabla \cdot (a_k q_k U_k) = \Gamma_k
\]

\[
\frac{\partial (a_k \rho_k U_k)}{\partial t} + \nabla \cdot (a_k \rho_k U_k U_k) = -a_k \nabla p + \nabla \cdot (a_k \mathcal{F}) + a_k \rho_k g \\
+ \Gamma_k U_{ik} + M_{ik}
\]

\[
\frac{\partial a_k h_k}{\partial t} + \nabla \cdot (a_k \rho_k h_k U_k) = -\nabla \cdot (a_k q^* h_k) + \Gamma_k h_{ik} + q_{ik}
\]

where the subscript \( k \) indicates phase, which can stand for the gas or the liquid, \( a_k \) is the volume fraction of phase \( k \), \( \Gamma_k \) is the mass source gained by phase \( k \), \( U_{ik} \) is the interfacial velocity, \( M_{ik} \) is the interfacial momentum transfer, \( h_{ik} \) is the interfacial specific enthalpy, and \( q_{ik} \) is the interfacial heat transfer rate.

In annular-mist flow, the gas phase and the droplets have mutual interactions, and furthermore they both have interactions with the liquid film. The interactions between the three fields of the gas, the droplets, and the liquid film therefore must be taken into account at the same time. For instance, the phase mass source term \( \Gamma_k \) includes all the mass transfer between the three fields of the gas, the droplets, and the liquid film.

2.2.1. Source terms from the liquid film

The source terms for the liquid film model are also the sink terms for the gas phase or/and the droplets. For example, the evaporation of the liquid film means the phase change from the liquid film to the gas phase. The mass transferred in this process is treated as the mass sink for the liquid film and the mass source for the gas phase.

Since the transfer terms for liquid film from the gas core have been identified in previous sections for liquid film modeling, the corresponding model can be calculated straightforwardly as the source/sink terms for the gas core flow.

2.2.2. Interfacial transfer between gas and droplets

One important modeling requirement of the gas–liquid two-phase flow solver is the identification of the interfacial momentum transfer, with appropriate models for the applications [30–32]. The current application with droplets dispersed in gas flow differs from the more developed bubbly flow, and it is more similar to the particle flow. The drag force is the major driver to accelerate the droplets in the gas and it is calculated using the Schiller–Naumann model [33]. Usually the virtual mass force is negligible in particle or droplet dispersed flow, and the test calculation confirmed it. As a result, the virtual mass force is not calculated in the final model. The Favre Averaged Drag (FAD) model for turbulent dispersion is based on the Favre average operation of the original governing equations, with theoretical background, and therefore used for the current model [34]. State-of-the-art development for the lift force in droplet dispersed flow is not well established for two-fluid model, and different results could be obtained with different models [35,36]. Furthermore, it has been a well-known issue for the lift force implementation in the wall-adjacent cells, with huge fluid velocity gradients. As a result, the lift force is not taken into account in the final model.

The interfacial mass transfer is the evaporation of the droplets, which is directly related to the interfacial heat transfer. The Ranz–Marshall model is widely used in the general two-phase gas–liquid flow solvers [37]. However, the experiments show that the interfacial heat transfer would be influenced due to the mass

Fig. 3. Schematic of the source terms for (a) mass, (b) pressure-based momentum, (c) stress-based momentum, and (d) energy.
transfer, which could be accounted for by one shielding factor based on the modified Spalding number \cite{38,39}. As a result, the Renksizbulut and Yuen \cite{39} model is selected in the final model.

For the calculation of interfacial transfers, we have to determine the interfacial area concentration. For droplet dispersed flow, the droplet coalescence and breakup are complex phenomena, and the formulation is not well established. Therefore, in the current model, only the droplet size change due to evaporation has been taken into account, using one dedicated transport equation modified from Yao and Morel \cite{40}.

### 2.2.3. Turbulence modeling

For the turbulence modeling, the standard k-epsilon model was used for both the gas phase and the droplets. As for the turbulent heat transfer, the experiments and analysis show that the turbulent Prandtl number could be around 0.9, which is also used in the present formulation \cite{41}.

### 2.3. Coupling of the gas core flow with the liquid film

The overall solution procedure starts with the input, and then the liquid film calculation, as shown in Fig. 4. The liquid film calculation will prepare the source term information for the gas core flow, and then the gas core flow will also prepare the source term information to the liquid film. The solver is basically transient, which is appreciated for the future transient applications, although currently only the steady state results are used.

The major interaction of the gas core flow and the liquid film in the annular two phase flow is the evaporation, droplet deposition and entrainment. This means that the three fields of gas, droplets, and liquid film have interfacial transfers of mass, momentum and energy.

For simplicity, the mass transfer mechanism is explained here as an example. For the gas field, there is mass source from evaporation of the liquid film. For the liquid film, there is mass source from the droplet deposition. For the droplets, there is mass source from entrainment of the liquid film.

### 3. Criterion of dryout occurrence

A stable dry patch forms when all the forces acting on the leading edge of the liquid film are in balance \cite{4–6}. The forces on the liquid film include mainly the stagnation pressure force, the surface tension force, the thermo-capillary force, the vapor thrust force, and the drag force \cite{5}.

Furthermore, the main parameters that govern the dryout phenomena can be identified based on the mechanistic analytical model \cite{6}. Correlations with robust and convenient applications could be developed using the existing experimental data \cite{6}.

In the current model, the critical film thickness criterion from system code MARS, which is based on the combination of the RELAP5 and the COBRA-TF codes, was employed \cite{22}. The critical film thickness is expressed as

\[
\delta_c = \left( \frac{q^w}{h_f g_f} \right)^{0.35} \frac{v_f g_f}{\sigma} \times 10^{-8.8 \left( \frac{\mu}{l_f} \right)^{0.017}}
\]

where \(\delta_c\) is the critical value for film thickness, \(q^w\) is the wall heat flux, \(h_f g_f\) is the latent heat of vaporization, \(G_f\) is the liquid film mass flux, \(v_f\) is the specific volume difference, \(\mu\) is the dynamic viscosity, and \(\sigma\) is the surface tension. The calculated critical film thickness has the order of 0.01 mm, and corresponds to the general trend as well known \cite{22}.

In the model implementation, local critical film thickness will be evaluated at each time step, and compared to the calculated film thickness. When the film thickness value is below the critical one, dryout occurs.

### 4. Modeling of post-dryout heat transfer

When dryout occurs, there is no liquid film coverage on the wall, and the heat transfer between the wall and the fluid deteriorates, leading to wall temperature excursion. As shown in Fig. 5, heat transfer mechanisms could be identified as (1) wall-gas convective heat transfer, (2) gas-droplet interfacial heat transfer, (3)
wall-droplet direct contact heat transfer, and (4) thermal radiation between the wall, the gas and the droplet. Among them, the gas-droplet interfacial heat transfer has already been described in the previous sections in the two-fluid gas core modeling, using the Renksizbulut and Yuen [39] model. Other mechanisms will be described as follows.

4.1. Wall-gas convective heat transfer

There is actually no special work needed here, since the convective heat transfer at any wall boundaries is calculated according to the selected turbulence model and corresponding near wall treatment. As described in the previous sections, the standard k–ε turbulence model, with wall function method was used in the current model. As for the energy equation, the similar wall function analogy was taken to calculate the wall temperature [41–44]. As one of the most popular wall functions, the Jayatilleke [43] model was taken as the reference model, expressed as

\[ \Theta^+ = Pr_f \left( \frac{\ln \theta^+}{\kappa} + P \right) \]  \hspace{1cm} (9)

\[ P = 9.24 \left( \frac{Pr}{Fr^{0.75}} \right) \left( 1 + 0.28 \exp \left( -0.007 \frac{Pr}{Fr} \right) \right) \]  \hspace{1cm} (10)

where \( Pr \) is the turbulent Prandtl number, \( Pr_f \) is the fluid molecular Prandtl number, \( E \) is the wall function constant, \( \kappa \) is the von Karman constant, \( y^+ \) is the dimensionless wall distance, and \( \Theta^+ \) is the dimensionless temperature defined as

\[ \Theta^+ = \frac{T_w - T}{T_f} \]  \hspace{1cm} (11)

where \( T_w \) is the wall temperature, \( T_f \) is the characteristic temperature defined as

\[ T_f = \frac{q''}{\rho c_p u_f} \]  \hspace{1cm} (12)

where \( q'' \) is the wall heat flux, \( c_p \) is the specific heat capacity, and \( u_f \) is the friction velocity defined as

\[ u_f = \sqrt{\frac{T_w}{\rho}} \]  \hspace{1cm} (12a)

where \( \tau_w \) is the wall shear stress.

4.2. Wall-droplet direct contact heat transfer

Since the wall temperature is usually higher than the Leidenfrost point in the post-dryout regime, actually a thin vapor layer appears between the wall and the droplet when a droplet impinges on the wall. Based on the droplet impact behavior and deformation, during the contact residence time, a model has been developed to account for the heat transfer between the wall and the droplet through the vapor conduction [24]. Recent experiment of direct droplet impinging on a horizontal plate and resulting analytical model have shown very similar results [45–47]. The Guo and Mishima [24] model is expressed as

\[ q_{d,w-d} = (T_w - T_{\text{sat}}) \left[ \frac{18}{32} \frac{\lambda^{1/3}}{\rho \mu \dot{d}_d \delta_{d}} h_{\text{w,d}} m_{\text{d}}^2 \right] \]  \hspace{1cm} (13)

where \( q_{d,w-d} \) is the wall-droplet direct contact heat transfer rate, \( T_{\text{sat}} \) is the saturation temperature, \( \lambda \) is the conductivity, \( m_{\text{d}} \) is the droplet deposition rate, \( d \) is the droplet diameter, \( \delta_{d} \) is the droplet volume fraction, and \( t_{\delta} \) is the droplet residence time, which is suggested as

\[ t_{\delta} = \pi \sqrt{\frac{\rho \delta d^3}{16 \sigma}} \]  \hspace{1cm} (14)

Compared to the wall-gas convective heat transfer, the wall-droplet heat transfer due to direct contact could be small in quantity, however, it is necessary to include it for the appropriate prediction of the wall temperature [24,47].

4.3. Thermal radiation between the wall, the gas and the droplet

Many previous work on post-dryout heat transfer neglected the thermal radiation compared to the wall-gas convection, as in the correlation development for instance [48]. In some situations, however, the thermal radiation may not be neglected [24,49]. Nevertheless, the accurate calculation of thermal radiation has not been well established, especially in the current two-phase mist flow regime, with generally two issues. One is the solving of the radiative transfer equation (RTE), with recent development on finite volume discrete ordinate method (DOM), which needs large computations. The other issue is the identification of the medium properties, which is very complicated, varying with radiation spectrum and composition [50].

Although the simulation results show the importance of thermal radiation in some situations, there is no experimental validation, and the employed radiative properties have high uncertainties [49]. As a result, the thermal radiation is not included in the current model. Nevertheless, the thermal radiation using DOM needs to be further developed in the future work.

5. Model validation

5.1. Experimental data

Post-dryout heat transfer experiments were carried out by Becker et al. [51] in the Royal Institute of Technology, with long vertical pipes of various inner diameters. Experimental data with typical boiling water reactor (BWR) operating conditions were selected as demonstrations for detailed analysis in this paper. The general data were shown in Table 1, and the measured inner wall temperature was shown in Fig. 6. The water flows upward and is heated from subcooled single phase to bubbly, slug, churn, annular-mist flow, and finally the post-dryout mist flow regimes. From the measurements of wall temperature distribution, we get the dryout position and the post-dryout wall temperatures, which are used for the validation of both the dryout occurrence and the post-dryout heat transfer modeling.

5.2. Case setup

Since the current CFD model is formulated for high quality two-phase flow from the annular-mist regime, the inlet boundary conditions were obtained using a one dimensional phenomenological model, which integrates from the onset of annular-mist flow to one point with appropriate film thickness, where the flow data were set as the inlet boundary conditions for the CFD calculation [52]. The inlet liquid film thickness and temperature are set for

<table>
<thead>
<tr>
<th>Table 1</th>
<th>General data on the post-dryout experiment.</th>
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<tbody>
<tr>
<td>Run</td>
<td>264</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>6.99</td>
</tr>
<tr>
<td>Inlet subcooling (K)</td>
<td>11</td>
</tr>
<tr>
<td>Mass flux (kg/m² s)</td>
<td>1500.2</td>
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<tr>
<td>Wall heat flux (MW/m²)</td>
<td>0.766</td>
</tr>
</tbody>
</table>
the liquid film domain, while the two-phase droplet dispersed gas flow velocities and temperatures were also set as in general two-fluid CFD solvers.

One important thing is that, as described in above sections, the droplet phenomena including deposition and entrainment have to be treated separately, since there is no direct formulation. Various models have then been proposed based on experimental results and theoretical analysis [2,3,53–56]. In the current work, the deposition model from Hewitt and Govan [2] and the entrainment model from Lopez de Bertodano et al. [54] were used as the reference models.

The droplet deposition rate is calculated as

$$m_{dep} = k_d C$$  \hspace{1cm} (15)

where $C$ is the droplet concentration in the gas, and $k_d$ is the deposition transfer coefficient, which is calculated as

$$k_d \sqrt{\frac{\rho_D D_h}{\sigma}} = 0.18$$ \hspace{1cm} if \hspace{0.5cm} $C/\rho_k < 0.3$

$$k_d \sqrt{\frac{\rho_D D_h}{\sigma}} = 0.083(C/\rho_k)^{-0.65}$$ \hspace{1cm} if \hspace{0.5cm} $C/\rho_k > 0.3$

Based on the entrainment mechanism of the Kelvin–Helmholtz instability, Lopez de Bertodano et al. [54] described the entrainment rate as

$$m_{entr} = 0.766 \text{ MW/m}^2$$ \hspace{1cm} \text{[51]}.
We\textsubscript{g} is the gas Weber number, defined as

\begin{equation}
\text{We}_{\text{g}} = \frac{\rho_{\text{g}}^2 D_{\text{h}}}{\sigma}
\end{equation}

and Re\textsubscript{lf} is the liquid film Reynolds number, defined as

\begin{equation}
\text{Re}_{\text{lf}} = \frac{\rho_{\text{lf}} J_{\text{f}} D_{\text{h}}}{\mu_{\text{f}}}
\end{equation}

The critical Reynolds number Re\textsubscript{fc} of 80 was used for water applications.

Multi-block hexahedral meshing was employed, and the corresponding non-dimensional wall spacing with values between 30 and 150 was preferred, since the wall function approach was used in the turbulence modeling with regard to the wall. Mesh independence study has been performed, and the reference mesh was shown in Fig. 7.

5.3. Results and discussion

The simulation results for the wall and vapor temperatures with reference models have been shown in Figs. 8–11, together with comparisons to the experimental measurements. The reference models have been listed in Table 2. Generally both the predictions of the dryout occurrence positions and the wall temperatures give quite good agreement with the experimental data.

To illustrate the detailed profiles of the simulation results, the radial profiles of the vapor temperature, the droplet volume fraction, and the axial vapor velocity at four selected vertical elevations were shown in Figs. 12–14. The vapor temperature before dryout is

\[ m_{\text{ent}} = 4.47 \times 10^{-7} \left[ \text{We}_{\text{g}} \left( \frac{\Delta \rho}{\rho_{\text{g}}} \right)^{0.5} \left( \frac{\text{Re}_{\text{lf}}}{\text{Re}_{\text{fc}}} \right) \right]^{0.925} \left( \frac{\mu_{\text{g}}}{\mu_{\text{f}}} \right)^{0.25} \frac{\mu_{\text{f}}}{D_{\text{h}}}
\]
almost uniform, at the saturation temperature of the system pressure. Further downstream of the dryout point, the vapor temperature gradually increases, due to the direct convection heat transfer from the wall to the vapor. Large temperature gradient near the wall could be seen from the results. Generally the droplet volume fraction decreases in the bulk flow, due to the overall interaction of droplet evaporation, deposition, and entrainment. The vapor velocity increases gradually in the post-dryout region, because of the fluid mixture expansion from the droplet evaporation.

5.3.1. Dryout location

In the current model, the critical liquid film thickness was calculated locally for each liquid film cell. The calculated liquid film thickness was compared to the critical value in each iteration cycle, and then the updated dryout information was used to indicate the local status of dryout occurrence.

On the other side, the dryout location is also dependent on the local film thickness distribution, which relies on the accurate

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Table 2
Reference models for the current development.

<table>
<thead>
<tr>
<th>Models</th>
<th>Description</th>
<th>References</th>
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<tr>
<td>Deposition model</td>
<td>Eqs. (15) and (16)</td>
<td>Hewitt and Govan [2]</td>
</tr>
<tr>
<td>Entrainment model</td>
<td>Eq. (17)</td>
<td>Lopez de Berrodano et al. [54]</td>
</tr>
<tr>
<td>Dryout occurrence</td>
<td>Eq. (8)</td>
<td>Chun et al. [22]</td>
</tr>
<tr>
<td>Wall-gas heat transfer</td>
<td>Eqs. (9) and (10)</td>
<td>Jayatilleke [43]</td>
</tr>
<tr>
<td>Wall-droplet heat transfer</td>
<td>Eq. (13)</td>
<td>Guo and Mishima [24]</td>
</tr>
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</table>

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Fig. 11. Wall temperatures for Run 271: water at 7.01 MPa, pipe diameter 14.9 mm, pipe length 7 m, inlet subcooling 11.7 K, inlet mass flux 1000.9 kg/m² s, wall heat flux 0.765 MW/m² [51].

Fig. 12. Vapor temperature profiles for Run 271: water at 7.01 MPa, pipe diameter 14.9 mm, pipe length 7 m, inlet subcooling 11.7 K, inlet mass flux 1000.9 kg/m² s, wall heat flux 0.765 MW/m² [51].
calculation of the interaction between droplet deposition and entrainment. The dependence of the dryout location on the droplet deposition and entrainment models was shown in Fig. 15, using Run 271 results as an example. The reference model of Hewitt–Bertodano with Hewitt and Govan [2] deposition and Lopez de Bertodano et al. [54] entrainment models show better results for the dryout location. Generally the entrainment models from Hewitt and Govan [2] and Okawa et al. [3] give higher entrainment rate, which results in the early dryout occurrence. The deposition model from Okawa et al. [3], on the other side, shows less deposition compared to the reference model, which also leads to the early dryout occurrence. Although the previous droplet deposition and entrainment models gave reasonable results in the phenomenological modeling of annular flow for dryout prediction, more experimental work is still needed for the model development and validation, with regard to the model range of validity.

5.3.2. Post-dryout heat transfer

Although there have been advancement in the modeling of industrial applications involve the heat transfer together with the fluid flow, the accurate post-dryout mist flow modeling is still a changing issue, due both to the high wall temperature and temperature gradients, and to the involvement of droplet dispersion and evaporation.

As shown in Figs 8–11, shorter post-dryout distances were predicted in the Runs 264 and 270, due to the lower wall heat flux. As the wall heat flux increases, the post-dryout regions will propagate upstream gradually, and furthermore, the peak wall temperature will also increase. These characteristics could also be well represented in the predictions.

From the experimental data, just downstream of the dryout point, the wall temperature increases rapidly, due to the transition from the convective boiling heat transfer to the post-dryout regime. Further downstream, the wall temperature still increases slowly. At some points, however, the wall temperature starts to drop, because of the improved heat transfer condition due to droplet evaporation and mixture expansion.

The calculations show very sharp temperature increase downstream of the dryout point. This could be due to the transition boiling flow, which currently is not included in the models. The other reason could be the axial heat conduction in the pipe wall, which may also be included in the further development of the models. On the other side, the calculated temperature shows longer decrease distances after the peak temperature, which may be because of the high evaporation rate of the droplets.

For the wall heat transfer, one interesting point is to evaluate the relative contribution of the wall-vapor convective heat transfer, the wall-droplet direct contact heat transfer, and the thermal radiation. As stated in previous sections, the thermal radiation is not included in the current model, and will be studied in the future work. Since it is well believed that the wall-vapor convective heat transfer dominates the wall heat release, calculations with and without wall-droplet direct contact heat transfer were conducted, and the wall temperature results for Run 271 were shown in Fig. 16. As could be observed, the calculations with the wall-droplet direct contact heat transfer included, generally give lower wall temperatures. This could be explained as follows. The wall-droplet heat transfer shares one part of the wall heat flux, and then it directly evaporates the droplets.
evaporation process, on the other hand, accelerates the vapor and improves the wall-vapor convective heat transfer. Both effects decrease the wall temperature. However, the wall temperature change is not significant, which coincides with the general judgment. Actually the maximum contributions of the wall-droplet direct heat transfer using Guo and Mishima [24] and Lelong et al. [46] models, are 0.51% and 2.04%, respectively. In consideration of the high total wall heat flux in the current experimental data, the wall-droplet direct contact heat transfer could be important, especially for lower wall heat flux situations.

6. Conclusions

An integrated CFD model, for diabatic high quality two-phase flow including turns-dryout regions from annular-mist regime to mist regime, has been developed. The model was based on a three-field description of droplets, gas, and liquid film for annular-mist flow, which incorporates both the pre and post dryout regions, with local models to determine the dryout occurrence. The thin liquid film model was coupled to the gas core flow model, which is described using the Eulerian–Eulerian approach. The dryout occurrence was predicted using a critical film thickness model. For the post-dryout region, the various heat and mass transfer mechanisms between the wall, the gas phase, and the droplets were identified, including the wall-gas convective heat transfer, the droplet evaporation, the droplet-wall direct contact heat transfer, and the thermal radiation, to calculate the temperature of the wall and the fluid.

The model was used in the simulation of the post-dryout heat transfer experiment in a vertical pipe, and the calculation results show good agreement with the experimental measurements, both on the dryout locations and the wall temperatures. The dryout location is dependent on the corresponding droplet deposition and entrainment models, and also on the local dryout occurrence criterion models. Nevertheless, although the reference models give satisfactory results, these sub-models need to be further developed and validated. The various post-dryout heat transfer mechanisms were identified, and the relative contributions to the wall heat transfer were investigated. The wall-gas convective heat transfer is dominant, which coincides with the existing general judgment. On the other hand, the maximum contribution from the wall-droplet direct contact heat transfer is about 1%, in the current simulations. In consideration of the high total wall heat flux in the current experimental data, the wall-droplet direct contact heat transfer could be important, especially for lower wall heat flux situations.

The general CFD framework for prediction of dryout and post-dryout heat transfer has been built in the current work. This is also a starting point for further work, as identified in this paper. The sub-models involved will be further developed, including the local dryout criterion model and the thermal radiation, for example, to improve the modeling.

Conflict of interest

None declared.

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References
