An analytical model for predicting dryout point in bilaterally heated vertical narrow annuli

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Abstract Based on the droplet-diffusion model by Kirillov and Smogalev (1969, 1972), a new analytical model of dryout point prediction in the steam-water flow for bilaterally and uniformly heated narrow annular gap was developed. Comparisons of the present model predictions with experimental results indicated that a good agreement in accuracy for the experimental parametric range (pressure from 0.8 to 3.5 MPa, mass flux of 60.39 to 135.6 kg•m^{-2}•s^{-1} and heat flux of 5 to 50 kW•m^{-2}). Prediction of dryout point was experimentally investigated with deionized water upflowing through narrow annular channel with 1.0 mm and 1.5 mm gap heated by AC power supply.

Keywords Narrow annuli, Bilaterally heating, Dryout point, Critical quality, Annular flow

CLC numbers TL33, O359

1 Introduction

The researches on dryout type critical heat flux (CHF) have been extensively carried out during the last four decades for various geometries. Among these geometrical CHF studies, less investigation has been made for annulus geometries than for round tubes and bundles. Saito et al.[1] formulated a four fluid model to analyze flow characteristics and CHF in the annular flow regime in annuli. This very complex model was able to predict a general CHF trend, but failed to predict simultaneous CHF occurrence at both annulus surfaces.

No empirical correlations or analytical equations to predict the CHF and its locations in bilaterally heated annulus have been found in the literature. To develop a CHF model for bilateral heating, Kirillov and Smogalev[2,3] first derived the model for internally heated annuli. The objective of this work is to propose a new analytical model for dryout point prediction in bilaterally heated annuli under low mass velocity by using their models.

2 Evaluation of model

The following assumptions are necessary in order to analyze the annular flow under these conditions:

(1) The flow is steady and incompressible;

(2) The liquid film is uniform around the tube periphery;

(3) The channel is assumed to be uniformly heated.

Fig.1 shows that the formation of annular flow takes place between inlet test section and point '*a*'. From the point '*a*' to the point '*p*', droplets break away from the wavy surface of the film and are entrained in the core stream, partly as a result of interaction between the film and the core stream and partly as a result of boiling and evaporation of the film. Upon attainment of a certain film thickness, breakaway of droplets from the film ceases, which corresponds to the point '*p*'. The region from '*p*' to '*c*' is an annular two-phase flow regime with a fairly smooth film on the channel wall and a core stream consisting of steam with droplets of liquid in it. When evaporation occurs at the wall and the steam departing from the wall hinders droplets deposition, the value of the droplet mass flow rate 'w_d' , at which deterioration of mass transfer begins, will increase by a certain amount, depending on the intensity of evaporation. At '*n*' point, droplets deposition from the core stream onto the channel wall

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deteriorates markedly or ceases completely. As the temperatures of droplets and steam in the main core stream are assumed as the saturation temperature, the quantity of droplets in the core stream cannot change until the dryout occurs. At 'c' point, liquid film completely disappears and dryout occurs.

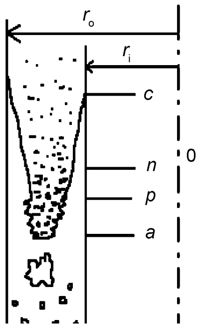

Fig.1 Two-phase flow patterns in bilaterally heated annuli. Region: a-liquid entrainment starts; p-liquid entrainment ceases and a fairly smooth liquid film begins; n-droplets deposition ceases; c-liquid film completely disappears and dryout occurs.

In the region 'n' to 'c' (i.e. to the section, where dryout occurs), the total mass flow rate at any section was composed of four parts. This will be determined by the relation:

$$W_{\mathrm{d}} + W_{\mathrm{g}} + W_{\mathrm{f,o}} + W_{\mathrm{f,i}} = W_{\mathrm{total}} \tag{1}$$

The liquid mass flow rate in the outer film may be estimated with the expression:

$$W_{\mathrm{f,o}} = 2\pi r_{\mathrm{o}}\delta_{\mathrm{o}}\rho_{\mathrm{f}}v_{\mathrm{f}} \tag{2}$$

Similarly, the liquid mass flow rate in the inner film can be used in the following form:

$$W_{\mathrm{f,i}} = 2\pi r_{\mathrm{i}}\delta_{\mathrm{i}}\rho_{\mathrm{f}}v_{\mathrm{f}} \tag{3}$$

Rearrangement of Eq.(1) with substitution of Eqs.(2) and (3), yields this equation:

$$W_{\mathrm{d}} + W_{\mathrm{g}} + 2\pi r_{\mathrm{o}}\delta_{\mathrm{o}}\rho_{\mathrm{f}}v_{\mathrm{f}} + 2\pi r_{\mathrm{i}}\delta_{\mathrm{i}}\rho_{\mathrm{f}}v_{\mathrm{f}} = W_{\mathrm{total}} \tag{4}$$

And dividing by W_{total}, we have

$$\frac{W_{\mathrm{d}}}{W_{\mathrm{total}}} + \frac{W_{\mathrm{g}}}{W_{\mathrm{total}}} + \frac{2\pi r_{\mathrm{o}}\delta_{\mathrm{o}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{W_{\mathrm{total}}} + \frac{2\pi r_{\mathrm{i}}\delta_{\mathrm{i}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{W_{\mathrm{total}}} = 1 \tag{5}$$

where $\dfrac{W_{\mathrm{g}}}{W_{\mathrm{total}}} = x$; so that

$$\frac{W_{\mathrm{d}}}{W_{\mathrm{total}}} + x + \frac{2\pi r_{\mathrm{o}}\delta_{\mathrm{o}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{W_{\mathrm{total}}} + \frac{2\pi r_{\mathrm{i}}\delta_{\mathrm{i}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{W_{\mathrm{total}}} = 1 \tag{6}$$

By differentiating with respect to 'z' (flow path length) direction, we obtain

$$\frac{\mathrm{d}\left(\dfrac{W_{\mathrm{d}}}{W_{\mathrm{total}}}\right)}{\mathrm{d}z} + \frac{\mathrm{d}x}{\mathrm{d}z} + \frac{\mathrm{d}\left(\dfrac{2\pi r_{\mathrm{o}}\delta_{\mathrm{o}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{W_{\mathrm{total}}}\right)}{\mathrm{d}z} + \frac{\mathrm{d}\left(\dfrac{2\pi r_{\mathrm{i}}\delta_{\mathrm{i}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{W_{\mathrm{total}}}\right)}{\mathrm{d}z} = 0 \tag{7}$$

In the region between 'n' and 'c', the droplets in the central vapor core at the saturated temperature of vapor, entrainment and deposition phenomena were ceased. Thus, the amount and size of droplets no longer happen to change until dryout occurs at the point 'c'. Therefore, 'W_{d}' in 'n-c' region was assumed as constant,

$\dfrac{\mathrm{d}\left(\dfrac{W_{\mathrm{d}}}{W_{\mathrm{total}}}\right)}{\mathrm{d}z} = 0$, so:

$$W_{\mathrm{total}}\frac{\mathrm{d}x}{\mathrm{d}z} + 2\pi r_{\mathrm{o}}\rho_{\mathrm{f}}v_{\mathrm{f}} \times \frac{\mathrm{d}\delta_{\mathrm{o}}}{\mathrm{d}z} + 2\pi r_{\mathrm{i}}\rho_{\mathrm{f}}v_{\mathrm{f}} \times \frac{\mathrm{d}\delta_{\mathrm{i}}}{\mathrm{d}z} = 0 \tag{8}$$

In the outside tube wall, due to evaporation, the liquid film thickness at the outer surface decreases in the direction of flow 'z', at the rate

$$\frac{\mathrm{d}\delta_{\mathrm{o}}}{\mathrm{d}z} = -\frac{q_{\mathrm{o}}}{h_{\mathrm{fg}}\rho_{\mathrm{f}}v_{\mathrm{f}}} \tag{9}$$

Similarly, the liquid film thickness at the inner surface decreases in the direction of flow 'z', at the rate

$$\frac{\mathrm{d}\delta_{\mathrm{i}}}{\mathrm{d}z} = -\frac{q_{\mathrm{i}}}{h_{\mathrm{fg}}\rho_{\mathrm{f}}v_{\mathrm{f}}} \tag{10}$$

Substituting (9) and (10) into (8):

$$\frac{\mathrm{d}x}{\mathrm{d}z} = \frac{2\pi r_{\mathrm{o}}q_{\mathrm{o}}}{h_{\mathrm{fg}}W_{\mathrm{total}}} + \frac{2\pi r_{\mathrm{i}}q_{\mathrm{i}}}{h_{\mathrm{fg}}W_{\mathrm{total}}}$$

$$\mathrm{d}x = \left(\frac{2\pi r_{\mathrm{o}}q_{\mathrm{o}}}{h_{\mathrm{fg}}W_{\mathrm{total}}} + \frac{2\pi r_{\mathrm{i}}q_{\mathrm{i}}}{h_{\mathrm{fg}}W_{\mathrm{total}}}\right)\mathrm{d}z \tag{11}$$

Integrating of Eq.(11) along the flow channel from 'n' to 'c', yields

$$x_c - x_n = \left(\frac{2\pi r_o q_o}{h_{fg} W_{total}} + \frac{2\pi r_i q_i}{h_{fg} W_{total}} \right) \int_n^c dz \tag{12}$$

Now, we can calculate the mass quality of dryout point, x_c when we know x_n and heated length between '*n*' and '*c*'.

2.1 Stable liquid film thickness

Formation of the annular two-phase flow regime takes place with a wavy film on the channel wall and liquid droplets in the core stream in the beginning of test section. From the point '*p*' to '*n*', droplets break away from the wavy surface of the film and are entrained in the core stream, partly as a result of boiling and evaporation of the film. Upon attainment of a certain film thickness, breakaway of droplets from the film ceases, which corresponds to the point '*n*'. The region from '*n*' to '*c*' is characterized by an annular two phase flow regime where liquid film is stable. The stable liquid film starts from '*n*' point, it is also mentioned as initial liquid film.[4] For the stable liquid film, δ_{st} is assessed from the Tippets[5,6] formula:

$$\delta_{st} = \frac{\sigma \left(1 + \frac{\rho_f}{\rho_g}\right)}{\tau \left[1 + \left(\frac{\rho_f}{\rho_g}\right)^{0.5}\right]^2} \tag{13}$$

where the shear stresses for inside and outside tube were assumed, after Knudsen and Katz[7] for single phase flow to be also valid for the annular flow regime:

For outside tube,

$$\tau_o = \frac{4\mu_g v_g \left(r_o^2 - r_m^2\right)}{r_o \left(r_o^2 + r_i^2 - 2r_m^2\right)} \tag{14}$$

For inside tube,

$$\tau_i = \frac{4\mu_g v_g \left(r_m^2 - r_i^2\right)}{r_i \left(r_o^2 + r_i^2 - 2r_m^2\right)} \tag{15}$$

where

$$r_m = \sqrt{\left(r_o^2 - r_i^2\right) / \left(2 \ln \frac{r_o}{r_i}\right)} \tag{16}$$

Rearrangement of Eq.(13) with the substitution of Eqs.(14) and (15) yields stable liquid film thickness for outside and inside tube equation as the following forms:

$$\delta_{st,o} = \frac{r_o \left(r_o^2 + r_i^2 - 2r_m^2\right) \sigma \left(1 + \frac{\rho_f}{\rho_g}\right)}{4\mu_g v_g \left(r_o^2 - r_m^2\right) \left[1 + \left(\frac{\rho_f}{\rho_g}\right)^{0.5}\right]^2} \tag{17}$$

$$\delta_{st,i} = \frac{r_i \left(r_o^2 + r_i^2 - 2r_m^2\right) \sigma \left(1 + \frac{\rho_f}{\rho_g}\right)}{4\mu_g v_g \left(r_m^2 - r_i^2\right) \left[1 + \left(\frac{\rho_f}{\rho_g}\right)^{0.5}\right]^2} \tag{18}$$

2.2 Heated length

At '*n*', a fairly smooth liquid films begin. The region from '*n*' to '*c*' is characterized by an annular two-phase flow regime with a fairly smooth film on the channel wall and a core stream consisting of steam with droplets of liquid in it. And then, evaporation occurs at the wall and at the point of '*c*' the liquid film dries out on the channel wall. From mass conservation, we can know the liquid mass flow rate into the '*n*' section at the condition of channel wall surface heated by heat flux '*q*' via the heated length from '*n*' to '*c*', L_{nc}. At the section of '*c*', the liquid film disappears, which is termed as dryout phenomenon. Obviously, Liquid film flow rate at '*n*' section is $2\pi r \delta_{st} \rho_f v_f$.

Evaporation rate of liquid film at section from '*n*' to '*c*' is

$$\frac{2\pi q r L_{nc}}{h_{fg}}$$

At '*c*' point, liquid film disappears and dryout phenomenon occurs and thus,

$$2\pi r \delta_{st} \rho_f v_f = \frac{2\pi q r L_{nc}}{h_{fg}}$$

$$L_{nc} = \frac{h_{fg} \delta_{st} \rho_f v_f}{q} \tag{19}$$

By using Eqs.(17), (18) and (19), we can calculate the heated length of inside and outside tube from

'n'section to dryout point section separately.

The heated length for outside tube:

$$L_{nc,\mathrm{o}} = \frac{h_{\mathrm{fg}}\delta_{\mathrm{sto}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{q_{\mathrm{o}}}$$

$$L_{nc,\mathrm{o}} = \frac{1}{4} \times \frac{\rho_{\mathrm{f}}\left(1+\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)}{\left[1+\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{0.5}\right]^2} \times \frac{r_{\mathrm{o}}\left(r_{\mathrm{o}}^2+r_{\mathrm{i}}^2-2r_{\mathrm{m}}^2\right)}{\left(r_{\mathrm{o}}^2-r_{\mathrm{m}}^2\right)} \times \frac{h_{\mathrm{fg}}\sigma}{q_{\mathrm{o}}\mu_{\mathrm{g}}} \times \frac{v_{\mathrm{f}}}{v_{\mathrm{g}}} \qquad (20)$$

The heated length for inside tube:

$$L_{nc,\mathrm{i}} = \frac{h_{\mathrm{fg}}\delta_{\mathrm{sti}}\rho_{\mathrm{f}}v_{\mathrm{f}}}{q_{\mathrm{i}}}$$

$$L_{nc,\mathrm{i}} = \frac{1}{4} \times \frac{\rho_{\mathrm{f}}\left(1+\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)}{\left[1+\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{0.5}\right]^2} \times \frac{r_{\mathrm{i}}\left(r_{\mathrm{o}}^2+r_{\mathrm{i}}^2-2r_{\mathrm{m}}^2\right)}{\left(r_{\mathrm{m}}^2-r_{\mathrm{i}}^2\right)} \times \frac{h_{\mathrm{fg}}\sigma}{q_{\mathrm{i}}\mu_{\mathrm{g}}} \times \frac{v_{\mathrm{f}}}{v_{\mathrm{g}}} \qquad (21)$$

To replace the average ratio of liquid velocity 'v_{f}' to vapor velocity 'v_{g}', the following slip ratio equation[8] is assumed to be valid:

$$S = \frac{v_{\mathrm{g}}}{v_{\mathrm{f}}} = \left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{1/2} \qquad (22)$$

Therefore:

$$\frac{v_{\mathrm{f}}}{v_{\mathrm{g}}} = \left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}\right)^{1/2} \qquad (23)$$

Finally, the heated length of inside and outside tube from 'n' section to dryout point section can be determined as follows:

The heated length for outside tube:

$$L_{nc,\mathrm{o}} = \frac{1}{4} \times \frac{\rho_{\mathrm{f}}\left(1+\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)}{\left[1+\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{0.5}\right]^2} \times \frac{r_{\mathrm{o}}\left(r_{\mathrm{o}}^2+r_{\mathrm{i}}^2-2r_{\mathrm{m}}^2\right)}{\left(r_{\mathrm{o}}^2-r_{\mathrm{m}}^2\right)} \times \frac{h_{\mathrm{fg}}\sigma}{q_{\mathrm{o}}\mu_{\mathrm{g}}} \times \left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}\right)^{1/2} \qquad (24)$$

The heated length for inside tube:

$$L_{nc,\mathrm{i}} = \frac{1}{4} \times \frac{\rho_{\mathrm{f}}\left(1+\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)}{\left[1+\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{0.5}\right]^2} \times \frac{r_{\mathrm{i}}\left(r_{\mathrm{o}}^2+r_{\mathrm{i}}^2-2r_{\mathrm{m}}^2\right)}{\left(r_{\mathrm{m}}^2-r_{\mathrm{i}}^2\right)} \times$$

2.3 Vapor's mass quality of stable liquid film in the test section

In the test section, mass quality x_n of stable liquid film at the 'n' position can be calculated by:

$$x_n = \frac{j_{\mathrm{g},n}\rho_{\mathrm{g}}}{G_{\mathrm{total}}} \qquad (26)$$

where '$j_{\mathrm{g},n}$' is drift velocity of vapor at 'n' position. The dryout point in the smallest annulus occurred at the transition from annular to annular mist flow.[9] Based on the criterion for the onset of droplet entrainment by Ishii and Grolmes,[10] the vapor velocity for a rough turbulent film flow of a weakly viscous fluid, such as water, can be given by

$$j_{\mathrm{g},n} = \left(\frac{\sigma g\Delta\rho}{\rho_{\mathrm{v}}^2}\right)^{1/4} N_{\mu\mathrm{f}}^{-0.2} \qquad (27)$$

where

$$N_{\mu\mathrm{f}} = \frac{\mu_{\mathrm{g}}}{\left[\rho_{\mathrm{f}}\sigma\sqrt{\sigma/(g\Delta\rho)}\right]^{0.5}}$$

The criterion given by Eq.(27) is recommended for a film Reynolds number, Re_{f}, greater than 1635. Substituting (24), (25) and (26) into (12), we can obtain mass quality of vapor at the surface of the inside and outside tube where dryout occurred when bilateral heating.

2.4 Calculation process for dryout point

(1) Calculate the drift velocity of vapor, $j_{\mathrm{g},n}$, in the 'n' position of test section according to (27), consequently mass quality in the 'n' position of test section was obtained by using (26).

(2) Calculate the heated length of inside and outside tube from 'n' to each dryout point produced, $L_{nc,\mathrm{o}}$ and $L_{nc,\mathrm{i}}$ respectively by using (24) and (25).

(3) Compare heated length $L_{nc,\mathrm{i}}$ and $L_{nc,\mathrm{o}}$, if $L_{nc,\mathrm{o}}$ was less than $L_{nc,\mathrm{i}}$, it is proved that dryout point will produce first in the outside tube and if $L_{nc,\mathrm{o}}$ was greater than $L_{nc,\mathrm{i}}$, it is proved that dryout point will produce first in the inside tube. Mass quality of dryout point position in the inside and outside tube can be calculated by the following formulas:

For mass quality of dryout point position in the inside tube,

$$x_{c,\mathrm{i}} = x_n + \left(\frac{2\pi r_\mathrm{o} q_\mathrm{o}}{h_\mathrm{fg} W_\mathrm{total}} + \frac{2\pi r_\mathrm{i} q_\mathrm{i}}{h_\mathrm{fg} W_\mathrm{total}} \right) L_{nc,\mathrm{i}} \tag{28}$$

For mass quality of dryout point in the outside tube,

$$x_{c,\mathrm{o}} = x_n + \left(\frac{2\pi r_\mathrm{o} q_\mathrm{o}}{h_\mathrm{fg} W_\mathrm{total}} + \frac{2\pi r_\mathrm{i} q_\mathrm{i}}{h_\mathrm{fg} W_\mathrm{total}} \right) L_{nc,\mathrm{o}} \tag{29}$$

3 Results and dicussions

The present model has been verified by our experimental data because no database for dryout point in bilaterally heated narrow vertical annuli with low flow conditions has been found in open literatures. The experiments were carried out in the range of pressure from 0.8 to 3.5 MPa, mass flux from 60.39 to 135.6 kg•m^{-2}•s^{-1} and heat flux from 5 to 50 kW•m^{-2} with 1.0 mm and 1.5 mm gap of narrow annuli by using deionized water. From Fig.2, it is easy to determine the location of dryout point that occurred on the surfaces of both side tubes in bilaterally heating experiment. Fig.3 shows the comparison of experimental and calculated critical quality in 1.0 mm and 1.5 mm gap as a function of mass velocity for pressure 3.5 MPa, inside tube heat flux 44.5 kW•m^{-2} and outside tube heat flux 45.0 kW•m^{-2} respectivity. A good agreement has been found.

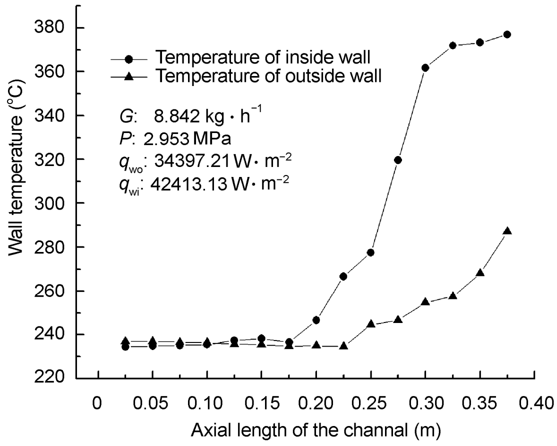

Fig.2 Dryout location in bilaterally heating experiment.

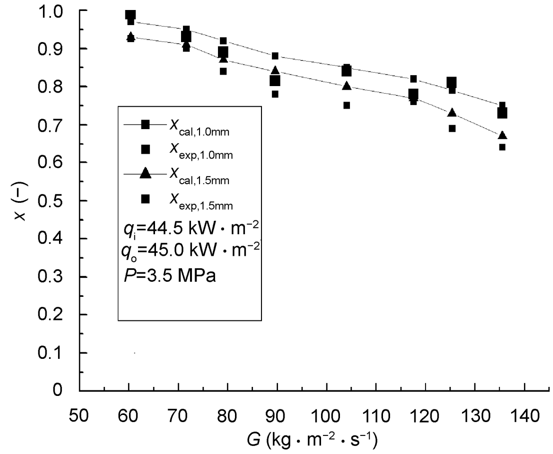

Fig.3 Comparison of critical quality between the experiment and the proposed model with 1.0mm and 1.5mm gap with different mass velocities.

The critical quality decreases with the increase of mass velocity. The velocity of the vapor core will increase with the increase of the mass velocity and the shear stress on the liquid / vapor interface will also increase. Then, the more liquid droplets will be entrained into the vapor core and the critical quality will decrease.

Fig.4 shows the comparison of critical quality between the present model and experiment. The mean error is 14.5% for 1.0 mm gap and 17.9% for 1.5 mm gap. The agreement between the experimental data and the present model for 1.0 mm and 1.5 mm gap are good. However, about 65% and 70% data of critical quality were overpredicted for 1.0 mm and 1.5 mm gap respectively within above error range, i.e. there are about 65% (1 mm) and 70% (1.5 mm) of critical quality values are larger than those of experimental data. The reason may be that the mass quality (at

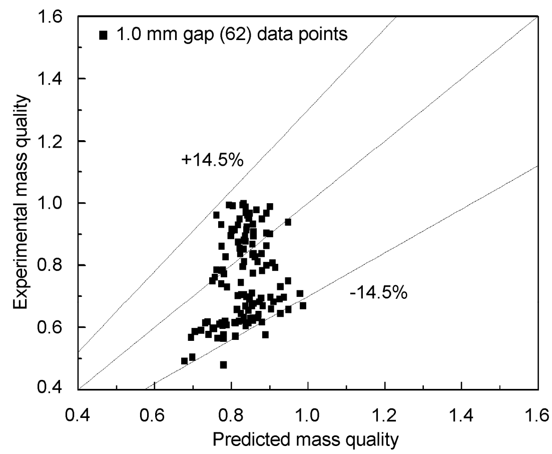

Fig.4(a) Comparison of critical quality for 1.0mm gap.

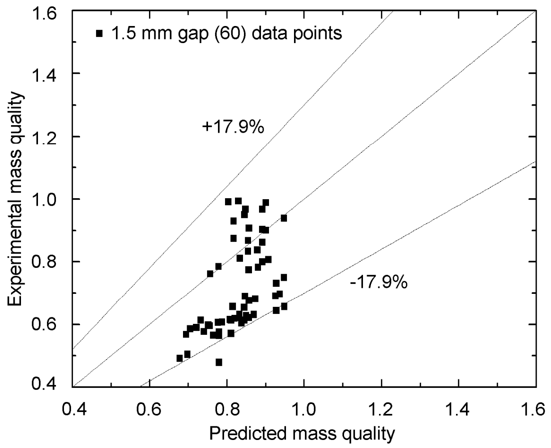

Fig.4(b) Comparison of critical qualityfor 1.5mm gap.

which deposition ceases) obtained by the proposed model is a bit higher than that of experiment.

4 Conclusions

A new analytical model for dryout point of critical quality in bilaterally heated annuli under low mass velocity is proposed by application of the Kirillov and Smogalev (1972) droplet-diffusion model for CHF occurrence at the inner annulus surface, which produces good predictions of the position of dryout point compared with the experimental data. The present paper suggested an analytical model in the parametric range of P=0.8~3.5 MPa, G=60.39~135.6 kg•m^{-2}•s^{-1} and q=5~50 kW•m^{-2}. The prediction method may not be valid beyond the above-mentioned ranges. Prediction of dryout occurrence for bilateral heating in vertical narrow annuli is a complex task and reliable methods proposed by previous researches are limited to the experimental conditions. Therefore, it is still needed to develop a more general predictive method of dryout which covers a wide range of flow conditions and various dryout mechanisms.

Nomenclature

G mass velocity (kg•m^{-2}•s^{-1})
g acceleration due to gravity (m•s^{-2})
h_{fg} latent heat of vaporization (kJ•kg^{-1})
j drift velocity (m•s^{-1})
L heated length (m)
$N_{\mu f}$ dimensionless viscosity, Eq.(27)
q heat flux (kW•m^{-2})
r radius (m)
S slip ratio
W mass flow rate (kg•s^{-1})
x mass quality

Greeks

δ liquid film thickness (m)
ρ density (kg•m^{-3})
υ velocity (m•s^{-1})
σ surface tension (N•m^{-1})
τ shear stress (N•m^{-2})
μ dynamic viscosity (kg•m^{-1}•s^{-1})

Subscripts

c critical
d droplet
f liquid
f,i liquid film of inside tube
f,o liquid film of outside tube
g vapor
i inner
m corresponds to radius of maximum flow velocity
n corresponds to quality at which deposition ceases
nc section 'n' to 'c'
st stable

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