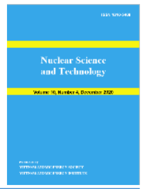
Nucl. Sci. and Tech., Vol.10, No. 1 (2020), pp. 21-30

Nuclear Science and Technology

Journal homepage: https://jnst.vn/index.php/nst



Evaluation of slip ratio correlations in two-phase flow

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Abstract: Critical flow is one of the essential parameters in LOCA accident analysis in which pressure difference is very high. Void fraction (α), in another term, slip ratio, s, is the key parameter that could affect critical flow prediction. Henry-Fauske (HF) model is the model for critical flow calculation existing in current computer codes such as MARS, RELAP, TRACE. However, the limitation of this model is slip ratio s=1. By modified the slip ratio correlation, the paper focuses on evaluating the HF model. Among the chosen correlations for slip ratio, Smith correlation is the best option for this purpose. The results in our paper showed that while the original Smith correlation with k=0.4 is suggested for horizontal tests, the modified one with k=0.2 could be applied for vertical tests.

Keywords: *Void fraction, slip ratio, critical flow.*

I. INTRODUCTION

The critical flow phenomenon takes place when liquid, gas, or mixture leaks from a system at high pressure to the ambient at lower pressure through a break such as in a break of safety valves or safety injection lines during a loss of coolant accident (LOCA). Understanding of break flow and its modeling are important things in a LOCA scenario. When the system approaches the critical flow condition, the discharge flow through the broken exit could reach a maximum value, and the flow rate becomes independent from the downstream pressure. Henry-Fauske (HF) [1] and Trapp-Ransom (TR) [2] are two leading applicable models for critical flow calculation in the current safety analysis codes among many models [3], [4]. However, as the application of these models is different, they should be used carefully while doing the calculation. HF model is only applicable for one component steam-water system. Furthermore, based on the assumption of the HF model, it could be applied to a well-mixed condition, thermal equilibrium. TR model, however, is applied to the two-component system, air-water. Together with this, to predict the critical mass flow, the HF model uses the upstream conditions, while the TR model bases on the throat conditions [5]. These models used a void fraction to predict the critical flow. Void fraction, defining as the fractional occupied area of the gas phase, is one important parameter for two-phase flow, based on which the component pressures, flow rate, and heat transfer are determined. Because the gas phase normally moves faster than that of the liquid phase, the void fraction could not be directly calculated from the mass flow rates of each

https://doi.org/10.53747/jnst.v10i1.28
Received 19 November 2019, accepted 25 February 2020

phase separately. Therefore, void fraction depends on the phase velocity ratio, so-called slip ratio. Slip ratio can be influenced by many variables, such as mixture quality, temperature and pressure, the direction of flow, circulation mode, wall friction Fauske [1], and the system geometry Kim [6]. Among those affected parameters, Kim [6] has suggested that the effect of diameter was the most important one influencing the critical flow. His explanation for this effect was related to the slip ratio.

This paper first reproduced the HF numerically. Our reproduced model for HF showed a good agreement in comparison with the selected database. Furthermore, based on Kim's suggestion, various slip ratio correlations were taken into account for evaluating the critical flow rate. However, the model of HF has only considered the slip ratio is unity. Therefore, our focus is on evaluated the HF model with different slip ratio correlations. Our result showed that Smith [7] correlation was the best candidate for predicting the critical flow. Based on his original k =0.4 value, the author modified this value. It could conclude that among chosen slip correlations, Smith correlation gave a good agreement while varying the k parameter for both horizontal and vertical tests. While the original Smith correlation could be used for the horizontal test, the modified k=0.2 for this correlation could be applied for a vertical one.

II. HENRY-FAUSKE CORRELATION

A. Henry-Fauske correlation

Henry-Fauske [1] suggested the model for a non-equilibrium model, using two continuity and one momentum equations of the single component flow (water–vapor system) without considering the wall shear stress and heat exchange. This model also developed using the following approximations:

- Same phase velocity (k=1)
- No mass transfer in the expansion
- Being in thermal equilibrium
- Isentropic expansion (s_g=s_l)
- The same liquid temperature.
- Polytropic expansion of vapor at the exit (as the ideal gas).
- The critical mass flow rate reaches a maximum value concerning the throat pressure, dG/dp_t =0.

Based on these approximations, the flow rate can be determined as follows:

$$G_{HF}{}^2 = \left[\frac{x_0 v_{gt}}{nP} + (v_{gt} - v_{f0})\left\{\frac{(1-x_0)N}{s_{gt}-s_{ft}}\frac{ds_{ft}}{dP} - \frac{x_0 c_{Pg}\left(\frac{1}{n}-\frac{1}{\gamma}\right)}{P(s_{g0}-s_{f0})}\right\}\right]^{-1} \tag{1}$$

Integrating the momentum equation from the stagnant to the throat locations:

$$(1-x_0)v_{f0}(P_0-P_t) + \frac{x_0\gamma}{\gamma-1}\left(P_0 v_{g0} - P_t v_{gt}\right) = \frac{\left[(1-x_0)v_{f0} + x_0 v_{gt}\right]^2}{2} G_{HF}{}^2 \tag{2}$$

Substitution eq. (1) into the eq. (2) and then rearrange this equation, the compact form can be obtained:

$$\eta = \left[\frac{\frac{(1-\alpha_0)}{\alpha_0}(1-\eta) + \frac{\gamma}{\gamma-1}}{\frac{1}{2\beta\alpha_t{}^2} + \frac{\gamma}{\gamma-1}}\right]^{\frac{\gamma}{\gamma-1}} \tag{3}$$

Where:

$$\eta = \frac{P_t}{P_0} \tag{4}$$

$$\beta = \frac{1}{\eta} + \left(1 - \frac{v_{f0}}{v_{gt}}\right)\left(\frac{(1 - x_0)NP_t}{x_0(s_{gt} - s_{ft})}\frac{ds_{ft}}{dP}\right) - \frac{c_{pg}\left(\frac{1}{n} - \frac{1}{\gamma}\right)}{(s_{g0} - s_{f0})} \quad (5)$$

and

$$\alpha_0 = \frac{x_0 v_{g0}}{(1 - x_0)v_{f0} + x_0 v_{g0}},$$

$$\alpha_t = \frac{x_0 v_{gt}}{(1 - x_0)v_{f0} + x_0 v_{gt}} \text{ and}$$

$$v_{gt} = v_{g0}(\eta)^{-\frac{1}{\gamma}}$$

For the given stagnant conditions of P_0 and x_0, by iteration until the η values in two Eq. (3) and Eq. (4) are converged, the critical pressure, P_t, can be obtained. The critical mass flow rate can finally be calculated.

B. Comparison of HF model

The main author's difficulty is that the MARS code is not commercial software. It is only allowable for Korean students to use its source code. Therefore, to modify the correlations in the HF model, the author has numerically reproduced this model based on the main equations given in the original papers [1] and compared the results with original ones. This work can be seen in detail in our paper [5]. Comparisons have been made for one component, steam-water. The critical mass flux data versus stagnation quality are taken from HF [1] at different pressures. Figs. 1, 2 and 3 show the comparisons between reproducing the HF model and the experimental data [1]. We found that this reproducing model gives similar results to the original ones.

From Figs. 1, 2, and 3, one can see that the HF model tends to be better at high pressure, and its result is under-predicted the data at low pressure. It means that this model in the current MARS code could be useful for high-pressure systems.

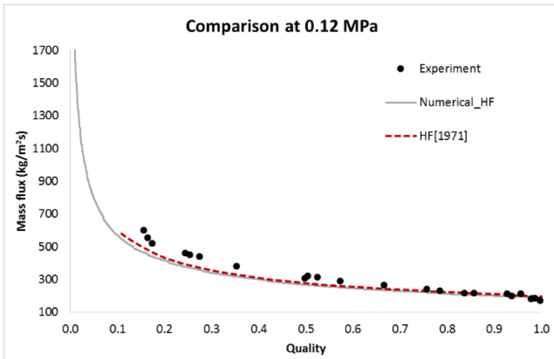

Fig. 1. Comparison of reproducing HF model with experimental data at 0.12MPa (17.6 psi) [1].

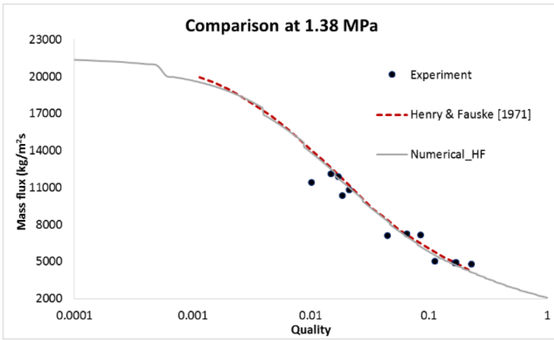

Fig. 2. Comparison of reproducing HF model with experimental data at 1.38MPa (200 psi) [1].

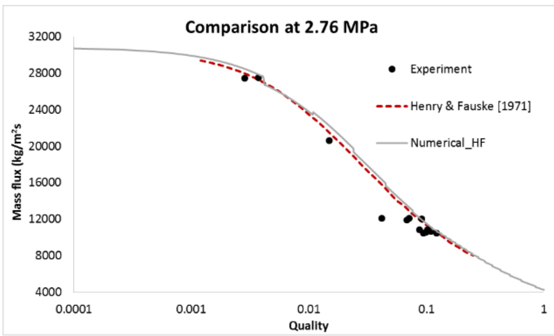

Fig. 3. Comparison of reproducing HF model with experimental data at 2.76 MPa (400 psi) [1].

III. SLIP RATIO CORRELATIONS

The estimation of hydrostatic, acceleration and friction pressure drops, and critical mass flow rate in the two-phase mixture is based on the knowledge of the void fraction, the relative volumes of gas and liquid phases at a given location. A huge number of empirical correlations and theoretical models for void fraction have been proposed in the past [8], [9]. The theoretical ones are mainly based on simplifying assumptions [1], [2], respect to the flow regime, and therefore the results cannot be of general applicability to two-phase phenomena such as boiling process including several different flow regimes, from bubbly to separate flow. Other models are developed based on a limited range of experimental conditions such as pressure, temperature or quality [7], [1], [10]. The void fraction depends on the phase velocity ratio, slip ratio in the general form [8], [9] as a function of quality (x), density (ρ), and viscosity (μ):

$$\alpha = \frac{1}{1 + A\left(\frac{1-x}{x}\right)^{b}\left(\frac{\rho_g}{\rho_f}\right)^{c}\left(\frac{\mu_f}{\mu_g}\right)^{d}} \tag{6}$$

In reality, only several types of reactors for gas/liquid exist. Moreover, one could be noted that the contribution of the viscosity component as shown in Table I, $\left(\frac{\mu_f}{\mu_g}\right)^{d}$, is less dominant. Therefore, this parameter could be negligible in the void fraction form. Void fraction correlations then could be reduced as follows:

$$\alpha = \frac{1}{1+A\left(\frac{1-x}{x}\right)^{b}\left(\frac{\rho_g}{\rho_f}\right)^{c}} \quad \text{or}$$

$$\alpha = \frac{1}{1 + s\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_f}\right)} \tag{7}$$

Where the slip ratio, s, is determined as follows:

$$s = A\left(\frac{1-x}{x}\right)^{b-1}\left(\frac{\rho_g}{\rho_f}\right)^{c-1} \tag{8}$$

Select the void fraction correlations having the form in Eq. (7), the author has compared them with the available experimental data (Table I).

Void fraction correlations related to slip ratio are listed in Table II.

Where: Re and We are Reynolds and Weber numbers, D is the equivalent diameter. A_{PRM}, A_{PA} and M parameters are determined as followings:

$$A_{PRM} = 1 + F_1\left\{\frac{y}{1+yF_2} - yF_2\right\},$$

$$F_1 = 1.578(Re)_f^{-0.19}\left(\frac{\rho_g}{\rho_f}\right)^{-0.22},$$

$$F_2 = 0.0273We_f\,(Re)_f^{-0.51}, y = \left(\frac{1-x}{x}\right)^{-1}\left(\frac{\rho_g}{\rho_f}\right)^{-1},$$

$(Re)_f = \frac{GD}{\mu_f}, We_f = \frac{G^2D}{\sigma\rho_f}$, G is the mass flux

$$M = 1+\log\left(\frac{\rho_f}{\rho_g}\right)/\log\left(\frac{1-x}{x}\right),$$

$A_{PA} = 0.735(\mu_f)^2(U_{SG})^2/\sigma^2$, σ is surface tension.

Table I. References related void fraction data measurement.

Reference	Diameter[mm]	Working fluid	Geometry	Pressure [psi]
Marchettere[11]	127	Steam-Water	Rectangular, vertical	114 - 600
Cook [12]	127	Steam-Water	Rectangular, vertical	114 - 600
Haywood [13]	12.7-38.1	Steam-Water	Pipe, horizontal	250 - 2100

Table II. Void fraction correlations.

Correlation	A	b	c	d
HEM [14]	1	1	1	0
Fauske [15]	1	1	0.5	0
Zivi [16]	1	1	0.67	0
Smith [7]	$k + (1-k)\sqrt{\dfrac{\frac{\rho_L}{\rho_G} + \frac{k(1-x)}{x}}{1 + k\left(\frac{1-x}{x}\right)}}$	1	1	0
Chisholm [17]	$\sqrt{1 - x\left(1 - {\rho_L}/{\rho_G}\right)}$	1	1	0
Spendding & Chen [10]	2.22	0.65	0.65	0
Hamersma & Hart [18]	0.26	0.67	0.33	0
Tuner & Wallis [19]	1	0.72	0.4	0.08
Lockhart & Martinelli [20]	0.28	0.64	0.36	0.07
Thom [21]	1	1	0.89	0.18
Baroczy [22]	1	0.74	0.65	0.13
Premoli [23]	A_{PRM}	1	1	0
Madsen [24]	1	M	-0.5	0
Chen [25]	0.18	0.6	0.33	0.07
Petalaz & Aziz [26]	A_{PA}	-0.2	-0.126	0

Table III. Slip ratio correlations.

Correlation	**Slip ratio, s**
HEM [14]	1
Fauske [15]	$\left(\frac{\rho_g}{\rho_f}\right)^{-1/2}$
Zivi [16]	$\left(\frac{\rho_g}{\rho_f}\right)^{-2/3}$
Smith [7]	$k + (1-k)\sqrt{\dfrac{\frac{\rho_L}{\rho_G} + \frac{k(1-x)}{x}}{1 + k\left(\frac{1-x}{x}\right)}}$
Spedding & Chen [10]	$2.22\left(\frac{1-x}{x}\right)^{-0.35}\left(\frac{\rho_g}{\rho_f}\right)^{-0.35}$
Hamersma & Hart [18]	$0.26\left(\frac{1-x}{x}\right)^{-1/3}\left(\frac{\rho_g}{\rho_f}\right)^{-2/3}$

Kim [6] has currently suggested that the slip ratio is the main parameter that could affect the diameter effect. In the past, some experimental work showed that critical mass flow rate increased while reducing the diameter of the throat (Sozzi and Sutherland [27], Chun and Park [28], Henry [29], Fauske [15]). The increase in the flow rate could be explained mainly based on the diameter effect. The raise of vaporization may be higher at the choking place with a decrease in sub-cooling upstream conditions at a very low sub-cooling temperature nozzle. It means that the slip ratio may increase for low sub-cooling upstream conditions. Several correlations of slip ratio were reviewed before taking them into account their critical flow predictions.

By comparing with the experimental data, void fraction correlations listed in Table I are evaluated. The six selected correlations are rewritten in the slip ratio form, as shown in Table III. Those slip ratio correlations will be evaluated in more detail using different pressures for both horizontal [11] and vertical [12],[13] tests.

A. Evaluations using horizontal test data

Chosen correlations are compared with Haywood data for a horizontal test in a high-pressure range from 1.72 to 14.5 MPa, as shown in Figs. 4, 5, and 6.

Even data changes in a high-pressure range, the original Smith's correlation remains the best candidate. We can conclude that Smith's correlation with his recommended k = 0.4 gives the best predictions.

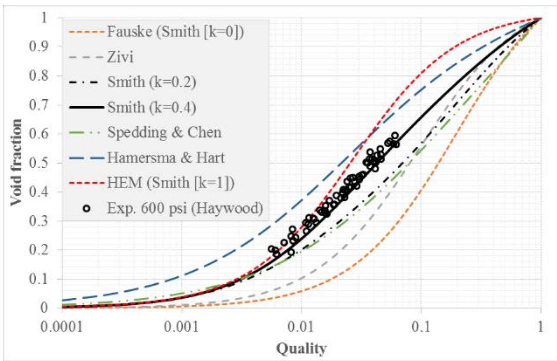

Fig. 4. Void fraction vs. quality in comparing with the Haywood data at 4.14 MPa (600 psi) [13].

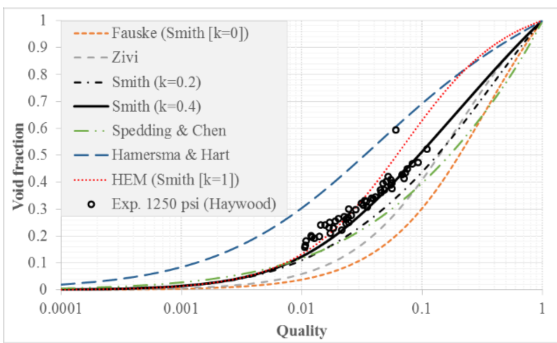

Fig. 5. Void fraction vs. quality in comparing with the Haywood data at 8.62 MPa (1250 psi) [13].

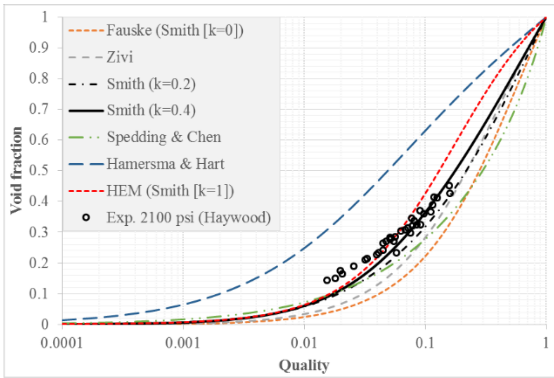

Fig. 6. Void fraction vs. quality in comparing with the Haywood data at 14.48 MPa (2100 psi) [13].

B. Evaluations using vertical test data

Marchettere [11] and Cook [12] performed experiments using the same vertical test facility, but at different pressures varied from 0.69 to 4.14 MPa. The predictions of chosen correlations are compared with the vertical test data, as shown in Figs. 7, 8, and 9:

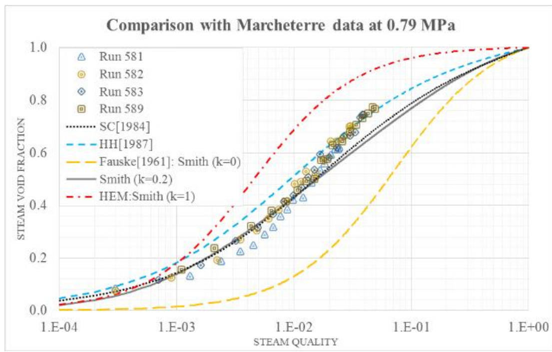

Fig. 7. Void fraction vs. quality in comparing with the experimental data at 0.79 MPa (114.5 psi) [11].

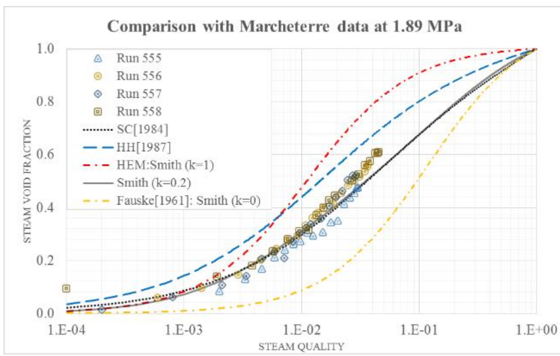

Fig. 8. Void fraction vs. quality in comparing with the Experimental data at 1.89 MPa (274.3 psi) [11].

The comparison of predictions between the chosen correlations and the experimental data from Marchettere [11] and Cook [12] show that the modified Smith's correlation with k = 0.2, as well as Speeding and Chen [10] one, are the best predictions.

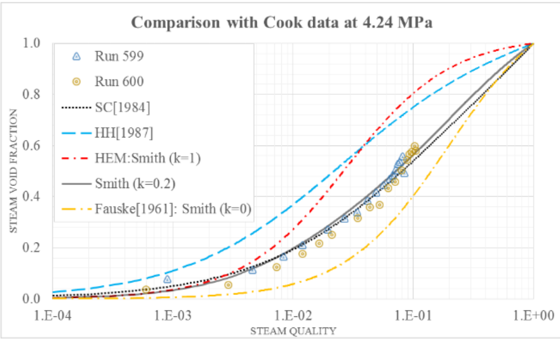

Fig. 9. Void fraction vs. quality in comparing with the experimental data at 4.24 MPa (614.4 psi) [12].

From these above comparisons, we could conclude that while the original Smith correlation with k=0.4 seems to be the best correlation for the horizontal test, its modification with k=0.2 could be the best correlation for the vertical test.

IV. EVALUATION OF SMITH'S CORRELATION

In the HF model [1], they developed their correlation in assuming that slip ratio equals 1. This slip ratio in the original HF model is modified by using the chosen slip correlations to predict the critical mass flux. The results are listed in Figs 10, 11, and 12. The evaluation process used data [1] measured at 0.12, 1.38, and 2.76 MPa.

The critical mass flux result of original HF is plotted in the continuous black line, and its modified one using Smith correlation with k = 0.4 is in the red long dash line. It should be noted that in Smith's correlation, the parameter k, which is the ratio between the mass liquid in the homogenous mixture and the total liquid mass, varies from 0 to 1. If k = 0, then slip ratio, s= $\left(\frac{\rho_g}{\rho_f}\right)^{-1/2}$, Smith correlation becomes Fauske one, in this case, the velocity heads of both liquid and gas are equal, $\rho_g u_g{}^2 = \rho_f u_f{}^2$. If k = 1, then s = 1, Smith correlation becomes HEM one, $u_g = u_f$. However, Smith's correlation was developed for the stratified flow with a homogeneous mixture phase and a liquid phase. In the original HF model, the slip ratio is a constant, s =1, which means that the mixture is well mixing in a homogeneous equilibrium state. By changing the chosen slip ratio correlations in the HF model, the predictions of mass flux at high quality are quite the same, while they become different at low quality.

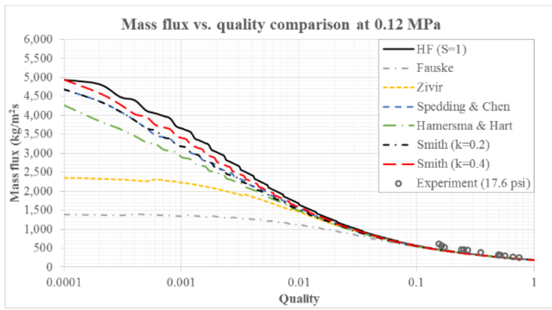

Fig. 10. Evaluation of critical mass flux for the HF model using the experimental data at 0.12 MPa [1].

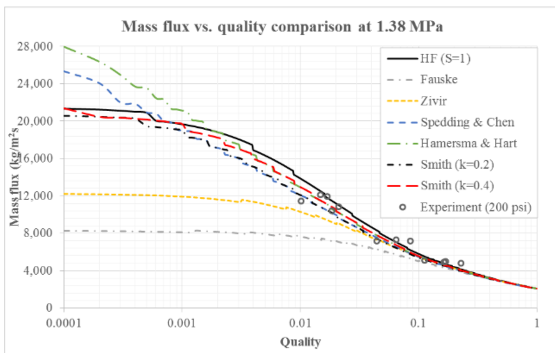

Fig. 11. Evaluation of critical mass flux for the HF model using the experimental data at 1.38 MPa [1].

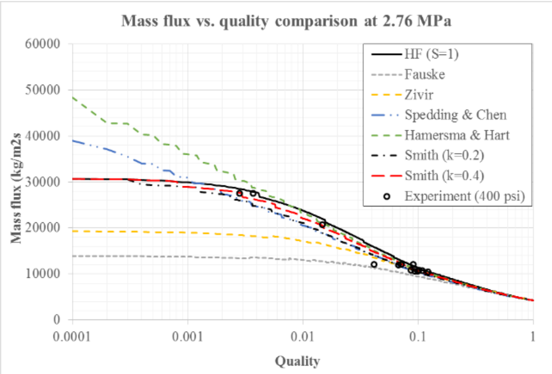

Fig. 12. Evaluation of critical mass flux for the HF model using the experimental data at 2.76 MPa [1].

At a quality higher than 0.1, the results at low pressure (Fig. 10) showed a similar result for all correlations. However, they become different while reducing qualities lower than 0.1. At hight pressures, Figs 11 and 12, the results using Spedding & Chen give a bad prediction at very low quality (less than 10^{-3}), while this correlation gave as good prediction as Smith one for vertical test data as can be seen in Figs. 7, 8, and 9.

Base on the evaluation work for the chosen slip correlations, we could conclude that the results given by Smith correlation with k=0.4 show the best critical mass flux prediction. This slip ratio correlation is based on simple assumptions for stratified flow. In the current computer codes for critical flow calculation, HF and TR models are still the most popular tools for critical flow predictions. HF model, however, keeps using the slip ratio of unity. Based on the result of our paper in predicting the critical flow rate, the modified slip ratio should be considered in the HF to get a better prediction.

V. CONCLUSIONS AND FUTURE WORK

Due to the limitation in software handling, the reproducing model of HF has been successfully evaluated. The reproducing model showed similar results with that calculated by using the original HF model. Slip ratio correlations, which correlate with critical mass flux predictions, were chosen and evaluated using both horizontal and vertical tests. From this work, we could conclude that the original Smith correlation with k=0.4 is the best choice for horizontal tests, while the modified one with k=0.2 is applicable for the vertical test. HF model was developed based on the slip ratio of unity. Therefore, we suggest modifying this ratio to get a better result for the two-phase critical flow simulation. Further data evaluation is needed for a wider range of pressure for both horizontal and vertical tests to get a clear picture of the best option for critical flow rate prediction.

NOTATION

c	Sound velocity (m/s)
C	Vitural mass (kg)
D	Diameter (m)
G	Mass flux (kg/m^2/s)
h	Enthalpy (J/kg)
k	liquid mass in the homogeneous mixture over total liquid mass
L	Length (m)
N	the partial phase change at the throat
s	Slip ratio, (u_g/u_f)
S	Entropy (J/K)
x	Quality
P	Presssure (MPa)
u_f	Liquid velocity (m/s)
u_g	Gas velocity (m/s)
v_f	Specific volume of liquid (m^3/kg)
v_g	Specific volume of gas (m^3/kg)
We	Weber number
Re	Reynolds number

Superscripts

0	Stagnant location
t	Throat location

g Gas component
f Fluid component

Greeks

α Void fraction
γ Isentropic exponent
λ The root of characteristic equation
η Critical pressure ratio
ρ_f Liquid density (kg/m^3)
ρ_g Gas density (kg/m^3)
μ_f Liquid viscosity (Ns/m^2)
μ_g Gas viscosity (Ns/m^2)

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