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A study of void fraction correlations used slip-ratio models

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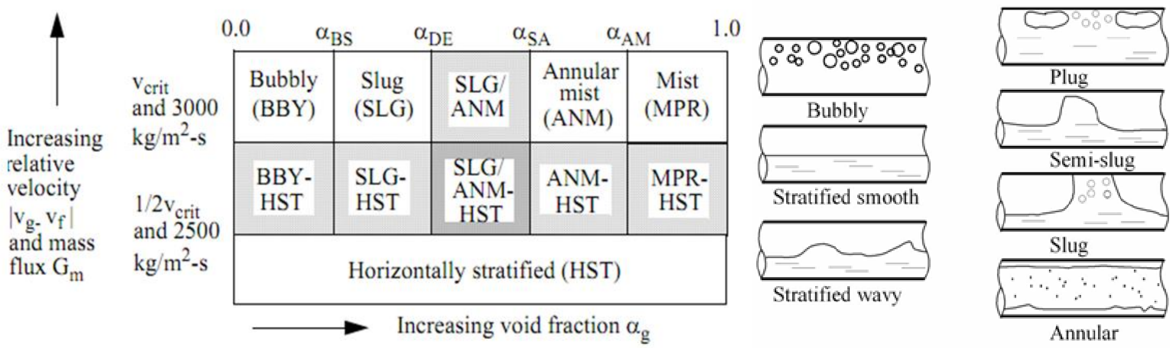
Abstract: Void fraction, the fraction of the channel cross-sectional area occupied by the gas phase, is an important parameter in thermal-hydraulic two-phase flow study. Based on that, the component pressures, flow rate, heat transfer, and flow pattern transitions are determined. However, this parameter cannot be computed directly from the flow rate of each phase as the gas phase is generally considered to move faster than the liquid phase in a two-phase flow. The purpose of this study is to evaluate the void fraction model by using different slip ratio models. The void fraction is affected by mixture quality, temperature, pressure, flow direction, circulation mode, wall friction, and system geometry. Theoretically, the void fraction is defined as a function of slip, quality, density, and viscosity ratios. At a given pressure, the variables are mainly determined using the steam table. To evaluate void fraction models, we employ experimental data measured at different pressures on both horizontal and vertical tests. The comparison results show that while the original Smith void fraction correlation with k = 0.4 is applicable to horizontal tests, the modified one with k = 0.2 applies to vertical tests.

Keywords: *Void fraction, slip ratio, horizontal test, vertical test, correlation.*

I. INTRODUCTION



a, Schematic of horizontal flow regime map *b, Horizontal flow regimes*

Fig. 1. Variation of void fraction with the different flow regimes

Estimating two-phase flow pattern transitions, heat transfer, and pressure drop requires knowledge of the void fraction, which ranges from 0 to 1. Void fraction represents the

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relative domain of gas and liquid phases at a given location in the two-phase mixture. It is commonly referred as the ratio of the cross-sectional area occupied by vapor to the total cross-sectional area of the conduit [[1]]. As depicted in Figure 1, this parameter is used in thermal-hydraulic codes, such as RELAP5, MARS, and TRACE, to predict flow regimes [[2],[3]]. The figure illustrates that each flow regime is defined by a single void fraction range.

Because of its essential role in the nuclear application, researchers have developed empirical correlations to predict void fractions and conducted experimental tests to measure the void fractions. Massive experimental work has been conducted under different operating conditions to determine void fraction [[4]-[5]]. Test facilities have been designed and constructed by varying the size and length of the tests under different conditions for vertical and horizontal tests [[6]-[8]]. Numerous empirical correlations and theoretical models for void fraction prediction have been developed [[7]-[13]]. Among numerous correlations, Butterworth [[7]] proposed his correlation as the function of three ratios, the ratio of qualities, densities, and viscosities, as expressed in Eq. (1):

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

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

$$s = A\left(\frac{1-x}{x}\right)^{b-1}\left(\frac{\rho_g}{\rho_f}\right)^{c-1}\left(\frac{\mu_f}{\mu_g}\right)^{d} \tag{2}$$

We can rewrite equation (1) in the following form:

$$\alpha = \left[1 + A\left(\frac{1-x}{x}\right)^{b}\left(\frac{\rho_g}{\rho_f}\right)^{c}\left(\frac{\mu_f}{\mu_g}\right)^{d}\right]^{-1} \tag{3}$$

Various studies have been conducted to determine the constants of A, b, c, and d. These correlations are listed in Table I. The parameter k in this table showing the fraction of liquid entrainment is the ratio of fluid mass in the homogeneous mixture and the total liquid mass.

Table I. Void fraction correlations

Correlation	A	b	c	d
HEM [[17]]	1	1	1	0
Fauske [[18]]	1	1	0.5	0
Zivi [[19]]	1	1	0.67	0
Lockhart & Martinelli [[21]]	0.28	0.64	0.36	0.07
Thom [[22]]	1	1	0.89	0.18
Tuner & Wallis [[23]]	1	0.72	0.4	0.08
Baroczy [[24]]	1	0.74	0.65	0.13
Smith [[6]]	$k + (1-k)\sqrt{\frac{\frac{\rho_L}{\rho_G} + \frac{k(1-x)}{x}}{1 + k\left(\frac{1-x}{x}\right)}}$	1	1	0
Premoli [[25]]	A_{PRM}	1	1	0
Chisholm [[26]]	$\sqrt{1 - x\left(1 - \rho_L/\rho_G\right)}$	1	1	0
Madsen [[27]]	1	M	-0.5	0
Spedding & Chen [[28]]	2.22	0.65	0.65	0
Chen [[29]]	0.18	0.6	0.33	0.07

Hamersma & Hart [[30]]	0.26	0.67	0.33	0
Petalaz & Aziz [[31]]	A_{PA}	-0.2	-0.126	0

Where A_{PRM}, M, and A_{PR} are the following terms:

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

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

$F_2 = 0.0273We_f\,(Re)_f^{-0.51}$, $y = \left(\frac{1-x}{x}\right)^{-1}\left(\frac{\rho_g}{\rho_f}\right)^{-1}$, $(Re)_f = \frac{GD.}{\mu_f}$, $We_f = \frac{G^2D}{\sigma\rho_f}$, G is the mass flux, Re and We are Reynolds and Weber numbers, D is the tube diameter;

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

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

The coefficient A in the Eq. (3) of all correlations listed in Table 1 are mainly constant, except for Smith [[6]], Chisholm [[26]], and Petalaz & Aziz [[31]], which are in complex form. Choosing a suitable correlation among the numerous correlations available for void fractions is challenging since most correlations have limitations. Their limitations differ in experimental test conditions or in simplifying assumptions in their developing process.

The vapor velocity of the tiny bubbles should tend to be the same velocity of liquid since their buoyancy is insignificant at very low void fraction. In reality, only few types of reactors for gas/liquid existed while main nuclear power plants use the steam-water system. Some correlations include the influence of viscosity, while others do not, as shown in Table I. Therefore, the impact of viscosity is less dominant than other parameters. Consequently, it may be negligible in our simulation. Based on this consideration, the most reasonable correlations are chosen. The selected void fraction correlations are written as slip ratio correlations listed in Table II. Note that if both c and b in Eq. (2) are equal to 1, the slip ratio equals a constant, A. Alternately, one can reduce its form to:

$$s = A\left(\frac{1-x}{x}\right)^{b-1}\left(\frac{\rho_g}{\rho_f}\right)^{c-1} \qquad (4)$$

The above investigation demonstrated that there are many correlations for void fraction prediction. Among the available correlations, which of the available correlations would be the most appropriate for predicting void fraction in horizontal/ vertical channels? The existing theoretical void fraction correlations are based on simplifying assumptions [[14]-[16]], regarding the specific flow regime. Therefore, the results cannot be applied to two-phase phenomena such as the boiling process, including several different flow regimes, from bubbly to separate flows. The main characteristic of varying flow regimes is the discontinuity at the boundary between flow regimes. This discontinuity may cause incorrect prediction results.

Table II. Remain void fraction correlations without viscosity component, d

Correlation	A	b	c	Assumptions	Exp. conditions
HEM [[17]]	1	1	1	$v_g = v_f$, thermal equilibrium, isentropic	Vertical test P:0.69-6.9 MPa; x: 0.0 - 0.2.
Fauske [[18]]	1	1	0.5	Same phase velocity, adiabatic flow	Horizontal test P: 0.28-2.48 MPa; x: 0.01-0.7.
Zivi [[19]]	1	1	0.67	No friction, no entrainment	Vertical test P:144-514 psi;

Smith [[6]]	$k+(1-k)\sqrt{\frac{\frac{\rho_L}{\rho_G}+\frac{k(1-x)}{x}}{1+k\left(\frac{1-x}{x}\right)}}$	1	1	Same the velocity head, thermal equilibrium	Horizontal test P: 1.73-14.5 MPa; x: 0.003-0.17.
Chisholm [[26]]	$\sqrt{1-x\left(1-{\rho_L}/{\rho_G}\right)}$	1	1		P: 1-7 MPa; x: 0.00-0.15
Spedding & Chen [[28]]	2.22	0.65	0.65	Isothermal, ideal equilibrium, $v_g \gg v_f$	Horizontal pipe, P: 0.1-.6 MPa;
Hamersma & Hart [[30]]	0.26	0.67	0.33	Small liquid holdup (high void fraction)	Horizontal test P: 0.1 MPa; x:0.005-0.04.

The homogenous equilibrium model (HEM) is the simplest model commonly used to calculate void fractions in two-phase flow [[17]]. This model is generated by assuming that liquid and vapor are in a homogeneous mixture flowing at the same velocity.

Zivi [[19]] correlation was developed based on the principle of minimum entropy production, which characterizes a steady-state thermodynamic process for the steam void fraction. The model was applied for annular flow with no entrained liquid in the vapor core and without wall friction assumptions. The identical Zivi is Moody's correlation [20] but uses the maximum flow rate. The Turner and Wallis [[23]] model is expressed in the void fraction form for turbulent-turbulent flow in separate cylinders. A similar Baroczy [[24]] correlation has also been modeled to fit into the void fraction correlation.

Chisholm [[26]] derived a slip model for annular flow based on the homogeneous flow idealization and an approximately equal frictional pressure drop in both phases. Interestingly, this correlation shows the correct thermodynamic limits at slip ratio approaching one as x tends to zero, and it becomes Fauske’s correlation, $s = \sqrt{\frac{\rho_l}{\rho_g}}$, when x tends to 1.

Spedding and Chen [[28]] have theoretically developed their correlation for the liquid holdup, R_g/R_f, against the volumetric flow rate ratio, Q_g/Q_f, in a two-phase flow. The final form of their correlation can be written as follows [[9]]:

$$\alpha = \left[1+2.22\left(\frac{1-x}{x}\right)^{0.65}\left(\frac{\rho_g}{\rho_f}\right)^{0.65}\right]^{-1} \quad (5)$$

Hamersma and Hart [[30]] developed their correlation using the based form of Eq. (3) with their suggested correlation [[9]]:

$$\alpha = \left[1+0.26\left(\frac{1-x}{x}\right)^{2/3}\left(\frac{\rho_g}{\rho_f}\right)^{1/3}\right]^{-1} \quad (6)$$

Smith [[6]] developed a semi-empirical void fraction model for annular flow with liquid entrainment in the vapor phase based on equal velocity heads of the homogeneous mixture core and the annulus liquid phase. He considered a liquid phase and a homogeneous mixed phase (vapor with liquid droplets), with an equalized velocity head assumption between the phases. His correlation expression was obtained in the homogeneous mixture by introducing the liquid entrainment factor, k, as shown in Table I. Smith correlation was empirically derived based on data sets, including steam-water and air-water flows in horizontal and vertical tubes. The parameter k varies in the range from 0 to 1. If is k equals to zero, the slip ratio equals $\sqrt{\frac{\rho_l}{\rho_g}}$, equal velocity heads between the vapor and liquid phases happened with no liquid entrainment. If the k becomes one, s = 1, there is no slip in the homogeneous mixture. For other values of k (0 < k < 1), the corresponding slip ratio varied between the two limits stated above, i.e., $1 < s < \sqrt{\frac{\rho_l}{\rho_g}}$. Smith mentioned that his correlation with the k = 0.4 porvied the most accurate experimental data predictions. He also indicated that his model could apply to the vertical and horizontal tests under all flow regimes while comparing the model result with experimental data. However, all flow regimes could not apply constant liquid entrainment of 40 % in the vapor core used in Smith's correlation. In addition, even this correlation was developed based on both horizontal and vertical data. It is better to consider the correlation for each flow direction separately because of the differences in typical flow characteristics.

Our current work [[32]] on slip ratio consideration suggested that the original Smith [[6]] slip ratio correlation with the entrainment factor of 0.4 could be used for the horizontal test. In contrast, a modified Smith correlation with the entrainment factor of 0.2 was suggested for the vertical test. Based on these slip ratio correlation suggestions, we conduct our work to see how the proposed correlations could affect the void fraction.

II. METHOD

Our research evaluates the void fraction of a two-phase steam-water mixture using the provided experimental data. The water and vapor properties are taken from the water steam table in our numerical simulations using the REFPROP library linked in our numerical method [[34], [35]]. The predicted void fraction of simulation results for each chosen correlation is compared with experimental data for horizontal [[35]] and vertical [[37], [37]] tests.

2.1. Experimental tests

In this research, our research group used data that were measured on Haywood's horizontal channel and Marcheterre and Cook's vertical channel. These systems were chosen because they use a steam-water mixture measured over a relatively wide range of pressure variations.

Haywood test [[35]] was performed to measure the void fraction or area dryness-fraction in the 38.1 mm bore horizontal pipe. The test used the steam-water system with its full heated length of 7.3 m or its partial heated height of 5 m. The experiment was conducted at a wide range of high pressures from 1.72 to 14.5 MPa to measure the void fraction using the gamma-ray beam method. The fully developed, separated flow in a horizontal pipe for this test was assumed to treat the two-phase mixed flow as a homogenous one. The diagrammatic test arrangement is shown in Fig.2.

Marchaterre [[37]] performed experiments on the same vertical test facility but at different pressures from 0.69 to 4.14 MPa. The apparatus, shown schematically in Fig. ***3***, consisted of a heated test section, a steam riser, a condenser, a liquid crossover to the downcomer, and the downcomer. The main flow passes the vertical test section to the liquid-vapor interface, where the steam separates and flows through the riser to the condenser. The remained liquid pours into the liquid crossover and rejoins the condensed vapor in the downcomer.

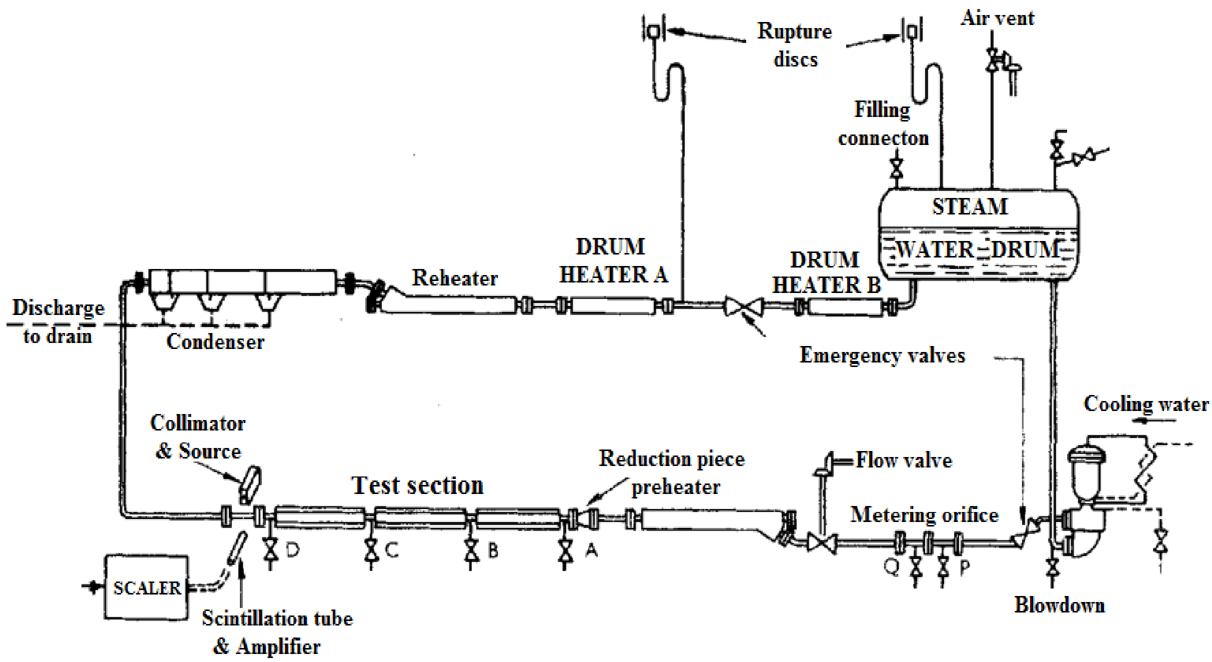

Fig.2. Diagram of Haywood test [[36]]

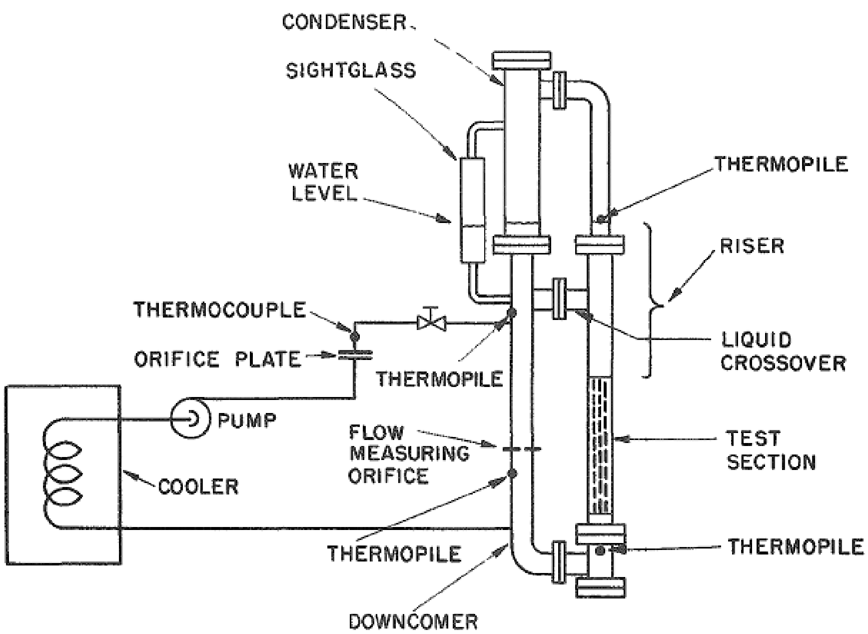

Fig. 3. Marchaterre [[37]] and Cook [[38]] test for a vertical steam-water system

The void fraction data were measured by Cook using the Radiographic technique with a maximum measurement error was 3.5 % [[38]]. A gamma-attenuation method was used for Marcheterre and Haywood tests to obtain void fractions data with a measurement error of 4%.

2.2. Tool

In addition to using the experimental test, numerical simulations have been used to evaluate chosen void fraction correlations by comparing them with experimental data. This process has been numerically carried out for selected void fraction correlations using the water steam table from the REFPROP library linked in our numerical method [[34], [35]]. The REFPROP provides vapor tables based on subroutines that calculate the thermodynamic and transport properties at a given temperature, quality (T, x), or pressure, quality (P, x) state. At a given pressure and inlet quality, the density, temperature, and viscosity ratio are calculated using Eq. (3) for each void fraction correlation in our numerical simulation. The predicted void fractions of chosen correlations are compared with experimental data.

III. RESULTS AND DISCUSSIONS

The entrainment factor in the Smith correlation varies in its range from the lower limit, 0, to the upper limit, 1. Our first investigation is to see how this parameter affects the void fraction results on horizontal and vertical channels. The survey result is applied to our simulation for each channel to predict void fractions of considered correlations and compare them with corresponding experimental data.

2.3. Investigation of the entrainment factor of the Smith for each channel

Haywood horizontal test data were used for this survey. The value of the entrainment factor, k of 0.4, presents the best fit when compared with the Haywood test data as shown in Fig. **4**.

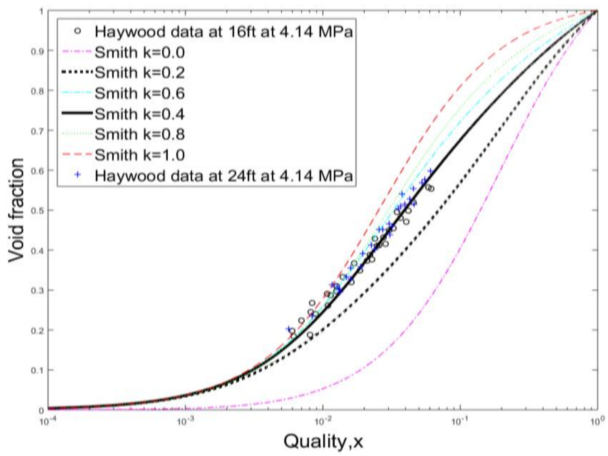

Fig. 4. Compare the void fraction prediction based on changing the entrainment factor k against horizontal data

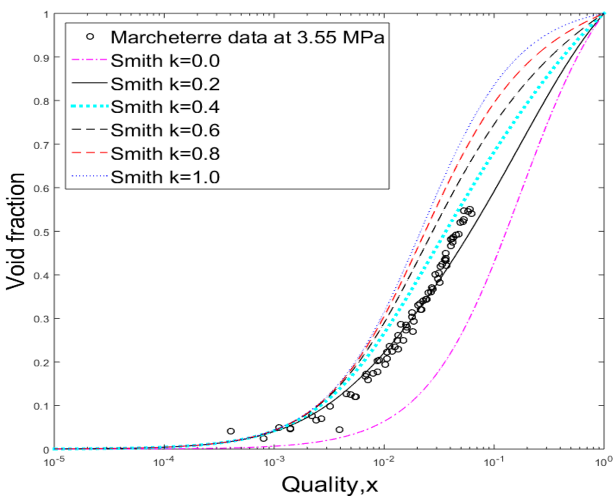

Fig. 5. Compare the void fraction prediction based on changing the entrainment factor k against vertical data

Similarly, Marchaterre test data were used for this survey. Among considered k values, the case with k=0.2 is the best fit compared to the Marchaterre test data, as shown in Fig. **5**. This survey confirms well our slip ratio model suggestion [[32]].

From the survey results and our previous paper [[32]] suggestion, the original entrainment factor of Smith, k of 0.4, is chosen for the horizontal channel. However, we suggest that our modified value of the entrainment factor, k of 0.2, be used for the vertical channel instead of Smith's original entrained factor, as Smith [[6]] recommended.

2.3. Predicted void fraction results of chosen correlations

We conducted our simulations using suggested slip correlations [[32]] which can be expressed as void faction correlations as listed in Table II, using Haywood and Marchaterre. In our simulation, the original Smith correlation with its entrainment factor of 0.4 is used for Haywood data. Our suggested model based on Smith modified entrainment factor of 0.2 is applied for evaluating Marchaterre data.

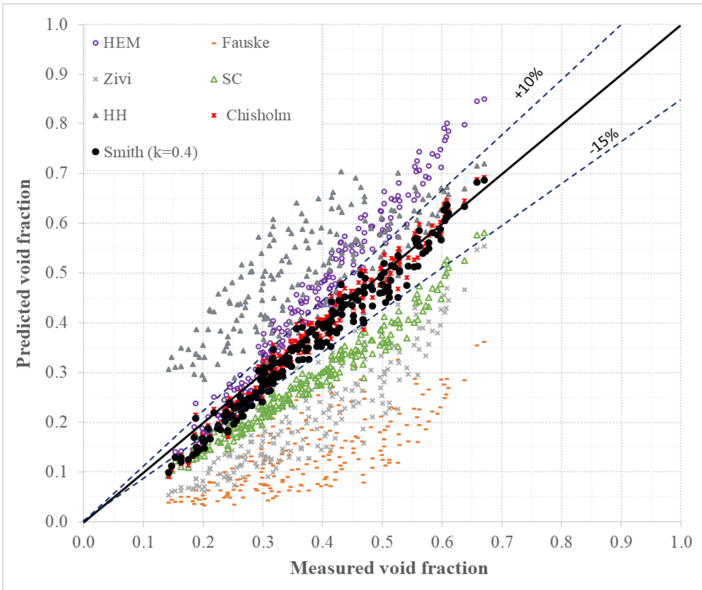

Fig. 6. Accuracy of void fraction models for horizontal test data

Figure 6 shows the summary of the chosen model accuracy using Haywood test data at different pressure in the range of 1.72 and 14.5 MPa. We could see that the measured void fractions were collected in high values (0.1 - 0.7). The figure showed that Smith's original correlation [[6]] with his recommended k of 0.4 gives the best predictions, which provide accuracy within 15%.

Figure 7 summarizes the chosen model accuracies using Marchaterre test data at pressure ranges of 0.69 to 4.14 MPa. Our suggested model based on modified Smith correlation (k of 0.2) shows the best predictions against these vertical test data in this comparison. The accuracy of the modified Smith correlation falls by 15%, except at low void fractions less than 0.1, as given in this figure. Our model based on modified Smith correlation with its entrainment factor of 0.2 could be applied to Marchaterre data in specific or vertical tests in general.

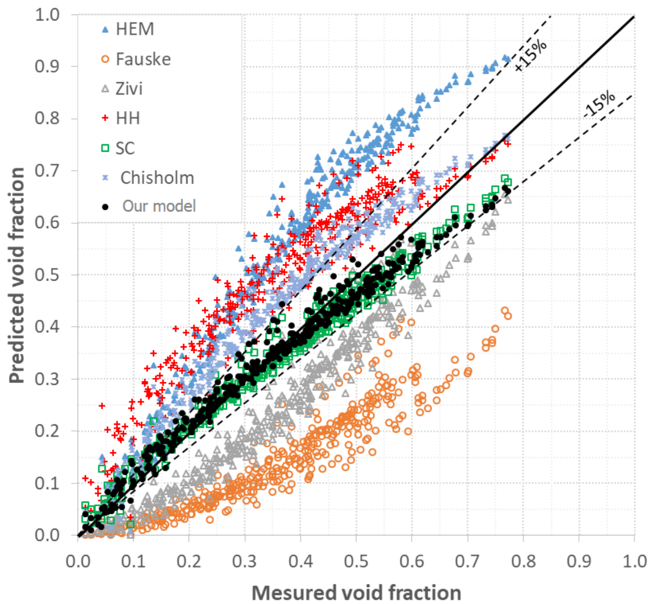

Fig. 7. Accuracy of void fraction models for vertical test data

The range of void fractions is defined according to different flow regimes in the RELAP5 code. In the illustration in Figure 1a for the horizontal flow in RELAP5 code, a void fraction value less than 0.25 is for bubbly flow, and from 0.25 to 0.5 is applied for the transition from bubbly to slug flow. The higher range of void fraction from 0.5 to 0.75 is for slug flow, and from 0.75 to 0.8 is for the transition flow from slug to the annular-mist flow, and the highest range of void fraction is applied for the drops or mist flow [[1]]. However, the Smith void fraction correlation [5] was developed based on a large amount of experimental data with a wide pressure range. His correlation with the water entrainment factor, k=0.4, the ratio of the mass of the liquid entrained in the gas core to the total mass of liquid, can be applied to calculate the void fraction for both horizontal and vertical channels without considering different flow regimes. The predicted void fraction using the original Smith correlation with his entrained factor k of 0.4 could be applied horizontal channel (Figure 6) but not to a vertical one. Our suggested model based on a modified Smith correlation with its entrainment factor of 0.2 (Figure 7) can be used to predict the void fraction in vertical channels.

III. CONCLUSIONS

Based on our previous work relevant to slip ratio correlation consideration, we use suggested correlations in evaluating the void fraction numerically. The available void fraction data from horizontal and vertical tests have been collected to assess chosen void fraction correlations. The simulation is based on the steam table taken from the REFPROP library, which provides the relevant properties of water and steam. Smith suggested that his correlation can be applied to predict the void fraction for horizontal and vertical channels without considering different flow regimes. However, our evaluation showed that his original correlation with its entrained factor k of 0.4 remained applicable for horizontal channels but not for vertical ones. The result of our study indicated that our suggested model, with the modified entrainment factor k of 0.2, could be used for predicting void fraction in the vertical test. Our numerical simulations interestingly show that Smith's correlation applies to horizontal and vertical tests with the corresponding entrained water factor k of 0.4 and 0.2.

In this study, we have used only the steam-water mixture experimental data. Therefore, different experimental data of gas-water mixture and refrigerants could be used to further evaluate our suggested models for both horizontal and vertical channels.

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NOMENCLATURE

α	Void fraction
k	Entrainment factor in Smith correlation
P	Pressure (MPa)
T	Temperature (K)
s	Slip ratio
x	Steam quality
ρ_f	Liquid density (kg/m^3)
ρ_g	Gas density (kg/m^3)
μ_f	Liquid viscosity (Pa.s)
μ_g	Gas viscosity (Pa.s)

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