Improvement of drift-flux correlations in MARS-KS for inclined two-phase flow: Model implementation and validation against air-water tests

Eunji Lee, Hyoung Kyu Cho*
Department of Nuclear Engineering, Seoul National Univ., 1 Gwanak-ro, Gwanak-gu, Seoul 08826
**Corresponding author: chohk@snu.ac.kr*

***Keywords : Drift-flux model, void fraction, inclined two-phase flow, air-water flow**

1. Introduction

Void fraction is a key parameter governing pressure drop, heat transfer, and flow regime transitions in nuclear reactor systems, and its accurate prediction directly affects the reliability of system thermal-hydraulic analyses.

Recently, interest in floating nuclear power plants (FNPPs) has increased. In FNPP systems, piping can experience continuous inclination and rolling motion. Under these conditions, the angle of gravity relative to the pipe changes, altering bubble distribution and gas-liquid relative velocity compared with stationary vertical conditions. Consequently, the void fraction can also vary with the inclination angle.

In system thermal-hydraulic codes such as MARS-KS, the two-fluid model is employed to solve the phasic momentum equations. The relative velocity and void fraction are primarily governed by the interfacial friction model representing interfacial momentum exchange. Within the interfacial friction package, the drift-flux approach is widely utilized as a closure relation for bubbly and slug flows. However, the drift-flux models implemented in MARS-KS were primarily developed for vertical or horizontal pipes and have not been sufficiently validated for various pipe inclinations relevant to marine applications. Therefore, their applicability to inclined two-phase flows needs to be evaluated to improve the predictive capability of MARS-KS under such conditions.

To account for inclination effects, various drift-flux correlations have been developed, including the Chexal and Lellouche (EPRI) [1], Bhagwat and Ghajar [2], and Dong et al. [3] correlations. These correlations have been developed for various working fluids and pressure conditions to predict void fraction and relative velocity.

The objective of this study is to implement these inclination-dependent drift-flux correlations into MARS-KS to improve its predictive capability for inclined two-phase flows. The experimental database used for model evaluation is limited to upward inclined air-water flows. The default MARS-KS model and the newly implemented models are evaluated against the available experimental data, and the drift-flux model that provides the best overall prediction is proposed as the most appropriate model for the considered conditions.

2. Interfacial friction model in MARS-KS

In MARS-KS, the gas and liquid phase velocities are calculated from phasic momentum conservation equations, which are given by [4]:

$$\alpha_k\rho_k\frac{\partial v_k}{\partial t}+\frac{1}{2}\alpha_k\rho_k\frac{\partial v_k^2}{\partial x} = F_P+F_B+F_w+F_\Gamma+F_I+F_{VM} \quad (1)$$

where $F_{P,}\,F_B, F_W, F_\Gamma, F_I,$ and F_{VM} are the pressure gradient, body, wall friction, interfacial mass transfer, interfacial friction, and virtual mass forces, respectively.

Among these terms, the interfacial friction force indicates the momentum exchange between the gas and liquid phases. The interfacial friction forces acting on the gas and liquid phases are calculated as follows:

$$F_{I,g} = \alpha_g\rho_g F_{Ig}(v_g - v_f) \quad (2)$$
$$F_{I,f} = \alpha_f\rho_f F_{If}(v_f - v_g) \quad (3)$$

Since the interfacial friction force describes momentum exchange between the two phases, the forces acting on the gas and liquid phases are equal in magnitude and opposite in direction. Therefore,

$$F_{Ig} = F_{If} = F_i \quad (4)$$

Based on this relationship, the interfacial friction force is then expressed as:

$$F_i = C_i|v_R|v_R \quad (5)$$

where C_i is the interfacial coefficient and v_R is the relative velocity between the gas and liquid phases. In MARS-KS, when the drift-flux method is applied to vertical bubbly and slug flow regimes, drift flux models are used in order to close Eq (5), while when the drag coefficient method is alternatively applied for other non-applicable regimes, drag coefficient and interfacial area models are necessary.

2.1 Drift-flux method in MARS-KS

The drift-flux model describes the relative motion between the gas and liquid phases by relating the gas velocity v_g to the mixture volumetric flux j as follows:

$$v_g = C_0 j + v_{gj} \quad (6)$$

where C_0 is the distribution parameter and v_{gj} is the drift velocity. In MARS-KS, this relationship is converted into the two-fluid momentum framework, where the interfacial friction coefficient C_i and relative velocity v_R are closed as:

$$C_i = \frac{\alpha_g \alpha_f^3 (\rho_f - \rho_g) g \sin\theta}{|v_{gj}| v_{gj}} \quad (7)$$

$$v_R = C_1 v_g - C_0 v_f \quad (8)$$

$$C_1 = \frac{1-\alpha_g C_0}{1-\alpha_g} \quad (9)$$

where v_g and v_f are the gas and liquid phase velocities, respectively, and θ is the pipe inclination angle relative to the horizontal plane.

The selection of the drift-flux correlation depends on the pipe diameter and mass flux. For the flow conditions considered in this study (small and intermediate diameter pipes under high up-flow rates), the EPRI drift-flux correlation, based on the Chexal-Lellouche correlation, is employed as the default model.

2.2 EPRI drift-flux model in MARS-KS

The drift-flux correlation implemented in MARS-KS is based on the Chexal-Lellouche model. However, the distribution parameter C_0 is represented by the vertical formulation C_{0v} only.

$$C_{0v} = \frac{L}{K_0 + (1-K_0)\alpha_g^r} \quad (10)$$

$$v_{gj} = 1.41 \left(\frac{(\rho_f - \rho_g)\sigma g}{\rho_f^2}\right)^{0.25} C_2 C_3 C_4 \quad (11)$$

Furthermore, the Chexal-Lellouche fluid parameter *L* is fixed to the steam-water formulation. Consequently, the default model does not account for inclination effects or air-water two-phase flow property characteristics.

3. Assessment of drift-flux model

3.1 Drift-flux model for inclined channel

To properly predict two-phase flow in inclined pipes, three representative drift-flux correlations were evaluated in MARS-KS: Chexal-Lellouche with air-water parameters, Bhagwat-Ghajar, and Dong et al. correlations.

For the Chexal-Lellouche correlation, the inclination interpolation F_r and dedicated air-water parameters $L_{air-water}$ were incorporated into MARS-KS to reflect inclined air-water characteristics:

$$C_0 = F_r C_{0v} + (1 - F_r) C_{0h} \quad (12)$$

$$F_r = \theta / 90° \quad (13)$$

where C_{0v} and C_{0h} are the vertical and horizontal distribution parameters, respectively. θ is the pipe orientation angle measured from the horizontal axis. The original Chexal-Lellouche correlation defines the pipe orientation angle from the vertical axis; therefore, F_r is transformed according to the angle convention adopted in this study.

The air-water parameters were calculated as

$$L_{air-water,v} = \min(1.15\alpha_g^{0.45}, 1.0) \quad (14)$$

$$L_{air-water,h} = \min(1.125\alpha_g^{0.6}, 1.0) \quad (15)$$

The Bhagwat-Ghajar correlation introduces inclination-dependent closures for both the distribution parameter and drift velocity:

$$C_0 = \frac{2 - (\rho_g/\rho_f)^2}{1 + (Re_{tp}/1000)^2} + \frac{\left[\left(\sqrt{\left[1+(\rho_g/\rho_f)^2 \cos\theta\right]/(1+\cos\theta)}\right)^{1-\alpha_g}\right]^{2/5} + C_{0,1}}{1+(1000/Re_{tp})^2} \quad (16)$$

$$v_{gj} = \left(0.35 \sin\theta + 0.45 \cos\theta\right) \sqrt{\frac{gD(\rho_f - \rho_g)}{\rho_f}} \left(1 - \alpha_g\right)^{0.5} C_2 C_3 C_4 \quad (17)$$

Similarly, the Dong et al. correlation incorporates the effect of inclination into the distribution parameter and drift velocity formulations:

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\rho_g/\rho_f} \quad (18)$$

$$v_{gj} = \begin{cases} \sqrt{2}\left(\frac{\Delta\rho g \sin\theta \sigma}{\rho_f^2}\right)^{1/4} & for\ 0 \le \langle j_g^+ \rangle / \langle j^+ \rangle \le 0.9 \\ \sqrt{2}\left(\frac{\Delta\rho g \sin\theta \sigma}{\rho_f^2}\right)^{1/4} \left(\frac{1-\langle j_g^+ \rangle / \langle j^+ \rangle}{0.1}\right) & for\ 0.9 < \langle j_g^+ \rangle / \langle j^+ \rangle \le 1.0 \end{cases} \quad (19)$$

The applicable ranges of the evaluated correlations are summarized in Table 1.

Table 1. Applicable range of each drift-flux correlation

Authors	Chexal-Lellouche (1992)	Bhagwat-Ghajar (2014)	Dong et al. (2020)
Working fluid	Steam-water, Air-water, Refrigerants	Air-water, Steam-water, Refrigerants, Air-oil, etc.	Air-water, Air-kerosene, Air-lube oil, Natural gas-water, Air-light oil
Pipe orientation [°]	-90 ~ +90	-90 ~ +90	0 ~ 90
Diameter [mm]	5 - 456	0.5 - 305	12.5 – 76.3
Applicable range	P: 0.1 – 18.0 MPa G: 0.01 – 5500 kg/m^{2}s	P: 0.1 – 18.1 MPa G: 10 – 8450 kg/m^{2}s ρ_f/ρ_g: 6 - 875	ρ_f/ρ_g: 35.1 - 839
Number of data [-]	7,705	8,255	3,343

3.2 Validation for vertical tests

To evaluate the performance of the default MARS-KS model (EPRI correlation) and the drift-flux correlations, a vertical upward air-water experimental database consisting of 54 experimental conditions and 88 data points was used. All experiments were conducted under atmospheric pressure and room temperature in vertical upward flow. Detailed experimental conditions are summarized in Table 2.

The void fraction, gas velocity, and liquid velocity were evaluated using the default drift-flux model implemented in MARS-KS, the Chexal-Lellouche model with air-water parameters, the Bhagwat-Ghajar and Dong et al. models. The predicted void fractions are compared with experimental data in Figs. 1-4, while the corresponding liquid and gas velocities are compared in Figs. 5 and 6, respectively. The validation for vertical flow conditions was conducted as a baseline assessment to verify the predictive performance of the default MARS-KS model and the additional drift-flux correlations before evaluating their applicability to inclined flows.

The default MARS-KS model tended to underpredict the void fraction in the low void fraction region. Although the liquid velocity was predicted relatively well, the gas velocity was generally overpredicted. In contrast, the application of the inclination-dependent drift-flux correlations improved the prediction of void fraction, particularly in the low void fraction region. The Bhagwat-Ghajar and Dong et al. models also showed improved predictions of gas velocity compared with the default MARS-KS model.

Table 2. Experimental database for vertical upward flow [5–8]

Experiment	Test case	Data point	L [m]	D [mm]	j_G [m/s]	j_F [m/s]
Hibiki (1999)	10	20	3.75	25.4	0.04-0.093	0.26-3.49
Hibiki (2001)	18	36	3.06	50.8	0.03-3.90	0.49-5.00
Dang (2017)	3	9	3.81	25.0	0.2-4.0	0.30, 1.00
Dang (2021)	23	23	3.59	12.7	0.08-2.30	0.30-2.00

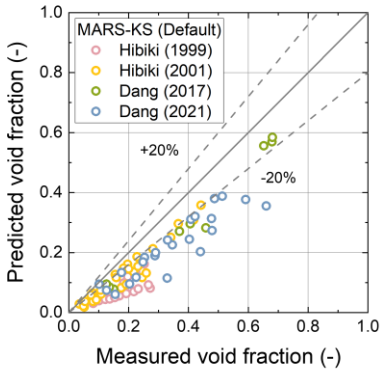


Fig. 1. Void fraction prediction by default MARS-KS

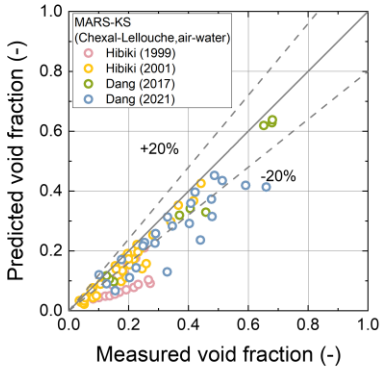


Fig. 2. Void fraction prediction by Chexal-Lellouche (air-water)

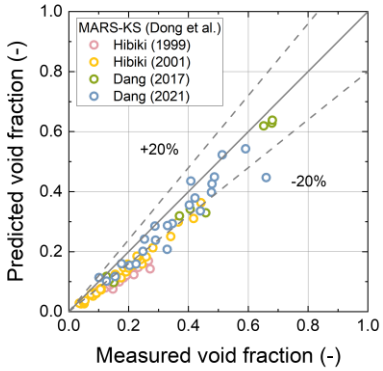


Fig. 3. Void fraction prediction by Dong et al.

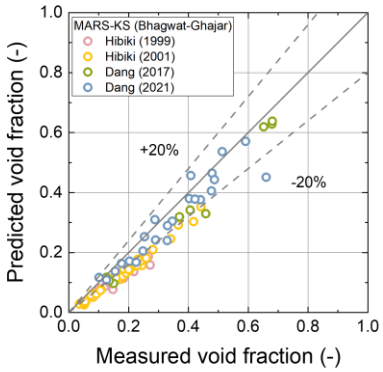


Fig. 4. Void fraction prediction by Bhagwat-Ghajar

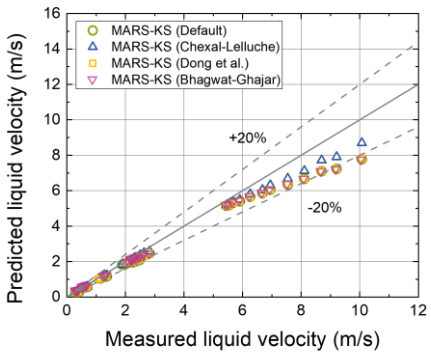


Fig. 5. Liquid velocity for each correlation

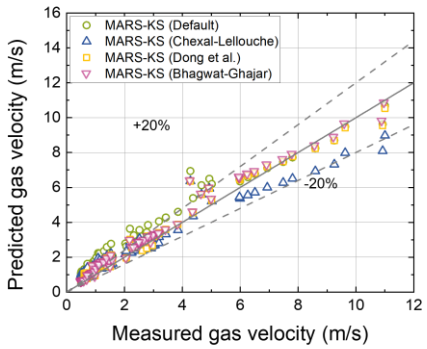


Fig. 6. Gas velocity for each correlation

3.3 Validation for inclined tests

To evaluate the performance of the default and newly implemented drift-flux correlations under inclined-flow conditions, an inclined upward air-water experimental database consisting of 301 test conditions was used. All experiments were conducted at atmospheric pressure and room temperature. Detailed experimental conditions are summarized in Table 3.

The default MARS-KS drift-flux model, the Chexal–Lellouche model with air-water parameters, the Bhagwat–Ghajar and Dong et al. models were evaluated by comparing the predicted void fraction and gas velocity with the experimental data, as shown in Figs. 7-10 and Fig. 11, respectively. For the gas velocity assessment, the comparison was conducted using the preliminary experimental data obtained by Ko et al. [12], and therefore the gas velocity comparison was limited to these data.

The default MARS-KS model and the Chexal–Lellouche model with air-water parameters tended to underpredict the void fraction in the low void-fraction region. In contrast, the Bhagwat–Ghajar and Dong et al. correlations predicted most of the experimental data within ±20%. Similar trends were observed for the gas velocity prediction. The default MARS-KS model and the Chexal–Lellouche model generally overpredicted the gas velocity, whereas the Bhagwat–Ghajar and Dong et al. correlations showed significantly improved agreement with the experimental measurements.

To further examine the effect of pipe inclination, the void fraction observed in the experiment of Ko et al. [12] was analyzed as a function of inclination angle, as shown in Fig. 12. The experimental data showed a decreasing trend in void fraction as the pipe was inclined from the vertical orientation.

According to the drift-flux relationship, the observed decrease in void fraction can be associated with an increase in drift velocity under the same flow conditions. Therefore, the inclination dependence of the drift velocity predicted by each correlation was examined in Fig. 13.

For the evaluated 13 mm channel diameter, the default MARS-KS, the Chexal–Lellouche, and the Dong et al. models predicted a decreasing trend in drift velocity as the inclination angle decreased, whereas the Bhagwat–Ghajar model predicted an increasing trend, which was consistent with the experimental observations.

This behavior can be attributed to changes in bubble behavior under inclined flow conditions. As illustrated in Fig. 14, bubbles tend to coalesce near the upper wall under inclined flow, increasing the population of larger bubbles. The resulting decrease in interfacial area concentration reduces the interfacial drag force and increases the gas velocity, leading to an increase in the drift velocity in the 13 mm diameter channel considered in this study. Among the evaluated correlations, the Bhagwat-Ghajar model best captures the physical behavior under inclined conditions and was therefore selected as the most appropriate model for the present study.

Table 3. Experimental database for inclined upward flow [9 – 12]

Experiment	**Case**	**D [mm]**	**Angle [°]**	**j_F [m/s]**	**j_G [m/s]**
Beggs (1972)	83	25.4, 38.4	55, 75, 90	0.0226 -5.54	0.250-24.1
Wiesche(2015)	40	13.0	45, 60, 75, 90	1.00-2.00	1.10-4.63
Bhagwat(2016)	114	12.5	45, 60, 75, 90	0.150-1.05	0.170-16.4
Ko (2025)	64	13.0	45, 60, 75, 90	0.63, 1.63	0.023-0.55

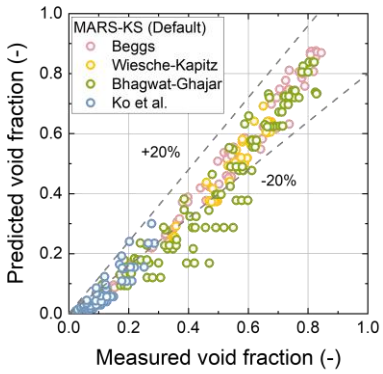


Fig. 7. Void fraction prediction by default MARS-KS

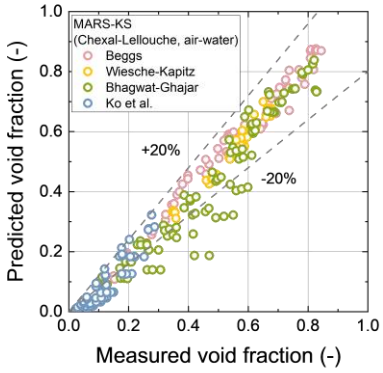


Fig. 8. Void fraction prediction by Chexal-Lellouche (air-water)

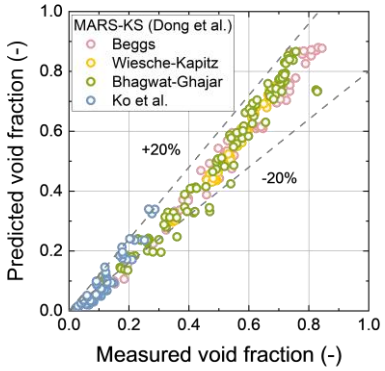


Fig. 9. Void fraction prediction by Dong et al.

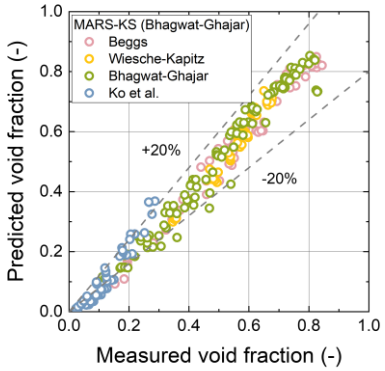


Fig. 10. Void fraction prediction by Bhagwat-Ghajar

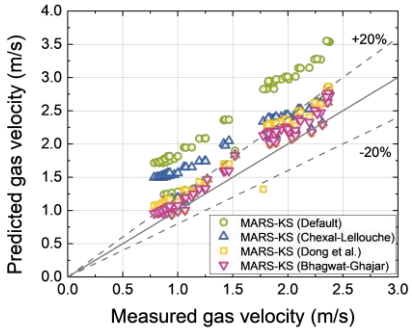


Fig. 11. Gas velocity for each correlation

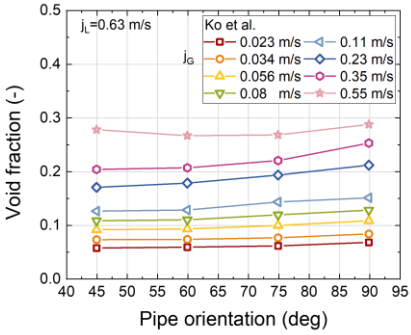
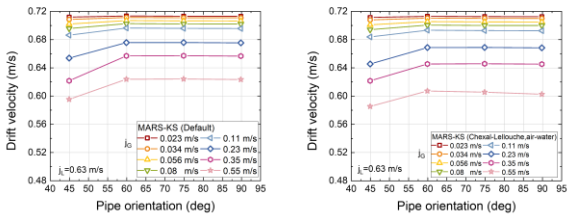
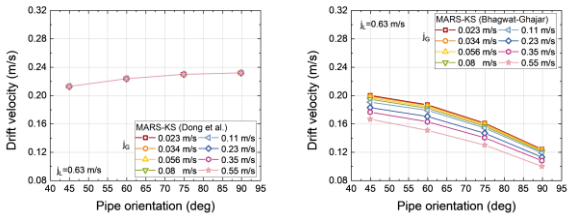


Fig. 12. Void fraction as a function of pipe orientation



(a) Default (b) Chexal-Lellouche (air-water)



(c) Dong et al. (d) Bhagwat-Ghajar

Fig. 13. Drift velocity for each correlation

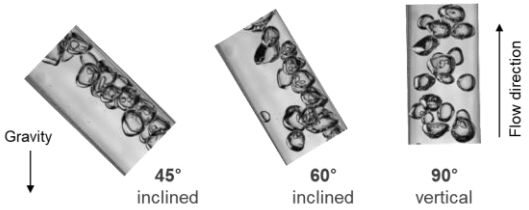


Fig. 14. Bubble behavior in inclined pipe

4. Conclusion

In this study, the performance of the drift-flux model implemented in MARS-KS for predicting void fraction in inclined air-water flow was evaluated. Three inclined flow correlations, namely the Chexal-Lellouche, Bhagwat-Ghajar, and Dong et al. correlations, were implemented in MARS-KS and assessed together with the default EPRI drift-flux model using vertical and inclined air-water experimental databases.

The vertical flow validation showed that Bhagwat-Ghajar and Dong et al. correlations improved the prediction of both void fraction and gas velocity compared with the default MARS-KS model. Under inclined flow conditions, the default MARS-KS and Chexal-Lellouche models tended to underpredict void fraction in the low void fraction region, whereas the Bhagwat-Ghajar and Dong et al. correlations showed better agreement with experimental data. Analysis of the drift-flux parameters further showed that the Bhagwat-Ghajar correlation reproduced the increase in drift velocity inferred from the experimental void fraction trend with decreasing inclination angle, while the other correlations predicted a decreasing trend.

These results indicate that the selection of an appropriate inclined flow drift-flux correlation can improve the predictive capability of MARS-KS for two-phase flow in inclined pipes. Although the present validation is limited to air-water experiments conducted

at atmospheric pressure and room temperature, the results of this study provide a basis for improving the modeling of two-phase flow under inclined conditions and for future analyses of rolling and high-pressure steam-water conditions in floating nuclear reactor systems.

REFERENCES

[1] B. Chexal, et al., A Void Fraction Correlation for Generalized Applications, Progress in Nuclear Energy, Vol. 27, No. 4, pp. 255–295, 1992.

[2] S. M. Bhagwat and A. J. Ghajar, A Flow Pattern Independent Drift Flux Model Based Void Fraction Correlation for a Wide Range of Gas–Liquid Two Phase Flow, International Journal of Multiphase Flow, Vol. 59, pp. 186–205, 2014.

[3] C. Dong and S. Rassame, Drift-flux correlation for upward two-phase flow in inclined pipes, Chemical Engineering Science, Vol. 213, 115395, 2020.

[4] KINS, MARS-KS Code Manual volume I: Theory Manual. 2018.

[5] T. Hibiki and M. Ishii, Experimental Study on Interfacial Area Transport in Bubbly Two-Phase Flows, International Journal of Heat and Mass Transfer, Vol. 42, No. 16, pp. 3019–3035, 1999.

[6] T. Hibiki, M. Ishii and Z. Xiao, Axial Interfacial Area Transport of Vertical Bubbly Flows, International Journal of Heat and Mass Transfer, Vol. 44, No. 10, pp. 1869–1888, 2001.

[7] Z. Dang, G. Wang, P. Ju, X. Yang, R. Bean, M. Ishii, S. Bajorek and M. Bernard, Experimental Study of Interfacial Characteristics of Vertical Upward Air-Water Two-Phase Flow in 25.4 mm ID Round Pipe, International Journal of Heat and Mass Transfer, Vol. 108, Part B, pp. 1825–1838, 2017.

[8] Z. Dang, G. Wang and M. Ishii, Two-Phase Interfacial Structure of Bubbly-to-Slug Transition Flows in a 12.7 mm ID Vertical Tube, International Journal of Heat and Mass Transfer, Vol. 165, Part A, p. 120556, 2021.

[9] H. D. Beggs, An Experimental Study of Two-Phase Flow in Inclined Pipes, Ph.D. Dissertation, The University of Tulsa, Tulsa, USA, 1972.

[10] S. A. D. Wiesche and M. Kapitz, Effect of Pipe Inclination on Void Fraction of Two Phase Gas-Liquid Flow, Proceedings of the ASME-JSME-KSME 2015 Joint Fluids Engineering Conference, Seoul, Korea, 2015.

[11] S. M. Bhagwat and A. J. Ghajar, Experimental Investigation of Non-Boiling Gas-Liquid Two Phase Flow in Upward Inclined Pipes, Experimental Thermal and Fluid Science, Vol. 79, pp. 301–318, 2016.

[12] H. Ko, et al., Experimental Investigation of Air-Water Two-Phase Flow through Inclined Circular Channel with Wire-Mesh Sensor: Preliminary Test, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 22–23, 2025.