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Derivation of New Non-Dimensional Parameter for Air-Water Counter Current Flow Limitation in Vertical Pipe

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1. Introduction

Counter current flow limitation (CCFL) is one of the most important phenomenon in the safety analysis of a pressurized water reactor (PWR). The CCFL phenomenon can occurs in the hot-leg and intermediated leg of a PWR during a small break of loss of coolant accident (SBLOCA).

In the counter-current two-phase flow in vertical tube, gas flows upwards through the center of the tube and liquid film flows downward. A shear stress is set up at the interface which retards the liquid film to flow downward. In a given liquid flow rate, there is a certain gas flow rate at which very large waves appears on the interface, the flow becomes chaotic, the gas pressure drop increases significantly and the upward flow of gas limits the downward flow of liquid at the top of the tube which is called CCFL or flooding [1].

The most widely used correlations for CCFL are Wallis type [1] and Kutateladze form [2]. The Wallis type correlation can be expressed as equation (1) while the Kutateladzee form can be expressed as equation (2).

$J_g^{*1/2} + mJ_l^{*1/2}=c$ ……… (1)

$Ku_g^{*1/2} + mKu_l^{*1/2}=c$ ……… (2)

Where, $J^*_g=J_g\rho_g^{1/2}/[gD(\rho_l-\rho_g)]^{1/2}$; $J^*_l=J_l\rho_l^{1/2}/[gD(\rho_l-\rho_g)]^{1/2}$; $Ku^*_g= J_g\rho_g^{1/2}/[g\sigma(\rho_l-\rho_g)]^{1/4}$; and $Ku^*_l= J_l\rho_l^{1/2}/[g\sigma(\rho_l-\rho_g)]^{1/4}$. The parameter J^*, Ku^* J, ρ, g, σ, D, m, and c, are the dimensionless flux of Wallis type, dimensionless flux of Kutateladze type, superficial velocity of fluid, density, gravitational acceleration, surface tension, diameter, slope, and gas intercept, respectively. The subscript l and g are liquid and gas phase, respectively.

It is reported in different literature that Wallis correlation is suitable for small diameter pipe and Kutataledge form is appropriate for large diameter pipe. Besides, it is seen from equation (1) and (2) that Wallis form has no surface tension effect while Kutataledge form has no diameter effect. Furthermore, neither correlations includes the viscosity effect and length effect on CCFL. So, it is necessary to develop a generalized CCFL correlation which includes density, viscosity, surface tension, gravitational acceleration, diameter, and length effect.

The main objectives of this study are to develop a new dimensionless parameter using dimensionless analysis, to validate the dimensionless number using experimental results from literature, and to propose a new CCFL correlation.

2. Derivation of New Dimensionless Number and Correlation

The most widely used dimensionless number to investigate the onset of CCFL phenomenon is Wallis parameter which is written as equation (3) [1].

$J^*_k=J_k\rho_k^{1/2}/[gD(\rho_l-\rho_g)]^{1/2}$ ………… (3)

There is a dimensionless number which includes surface tension, viscosity, density, and gravitational acceleration, known as Kapitza number (Ka). This Ka number is useful in the study of wave growth and instability in falling liquid film [3]. The Ka number can be written as equation (4).

$Ka=\sigma\rho_l^{1/3}/\mu_l^{4/3}g^{1/3}$ ………… (4)

To include the length effect on CCFL parameter, length over diameter ratio can be expressed as a dimensionless number in equation (5).

$R_{L/D}=L/D$ ………… (5)

By making the power of both equation (4) and (5) as 1/8 and divide the equation (3), a new dimensionless number can be found which is shown in equation (6).

$\Pi_k= J^*_k/[(Ka)\,(R_{L/D})]^{1/8}$
$= J_k\rho_k^{1/2}/[gD(\rho_l-\rho_g)]^{1/2}[L/D]^{1/8}[\sigma\rho_l^{1/3}/\mu_l^{4/3}g^{1/3}]^{1/8}$
$= J_k\rho_k^{1/2}\mu_l^{1/6}/\rho_l^{1/24}(\rho_l-\rho_g)^{1/2}g^{11/24}(\sigma)^{1/8}D^{3/8}(L)^{1/8}$ …………… (6)

Where, Π, J, ρ, μ, g, σ, D, L are the dimensionless flux of new parameter, superficial velocity of fluid, density, viscosity, gravitational acceleration, surface tension, slope, diameter, and length of the test section. The subscript k, l, and g are phase, liquid phase, and gas phase, respectively. This new dimensionless number not only includes the fluid properties but also includes diameter, and length of the tube.

The effects of intermolecular interaction by considering viscosity of liquid as a dynamic phenomenon and surface tension as a static phenomenon are included in this parameter. The superficial velocity of flooding shows inverse relationship with liquid viscosity in this new parameter which is logical because liquid viscosity affects friction factor. The superficial velocity of flooding also shows a proportional relationship with surface tension which follows the Kutateladze form. The viscosity and the surface tension exhibit opposite effects on the flooding velocity [4] which agrees with the new parameter. It can be mentioned that the effect of viscosity and surface tension is neglected in Wallis parameter considering little importance in annular counter current flow in vertical tube [1].

The superficial velocity of flooding increases with increasing tube length and diameter according to new parameter. The diameter effect follows Wallis form but the test section length has a proportional relationship with the superficial velocity of flooding which is a contradictory statement according to some previous literature. The flooding velocity decreases with increasing tube length and the effect is rather significant in the range of high liquid flow rates [5, 6]. Most flooding models incorporate a tube diameter effect, but the effect of the tube length, is not clear yet [4].

A correlation can be proposed by combining the square root of dimensionless number of liquid and gas phase as in equation (7), in which m and c are the negative slope and intercept in the straight line equation.

$$\pi_g^{*1/2} + m\pi_l^{*1/2} = c \qquad \text{……… (7)}$$

3. Validation of New Dimensionless Number and Correlation

To validate the new dimensionless number, experimental data from some literature are required to investigate the suitability of the new parameter in CCFL phenomenon. Since the new parameter includes length effect, experimental literature are required in which various length effects are used. An experimental study was conducted and flooding data [7] were compared with previous obtained data [5, 6] using Wallis parameter. In this study, those compared data [7] are chosen to examine the new parameter due to various length of the test section with same diameter. The experimental condition were air-water fluid in a vertical tube with the similar geometrical condition [7]. The square root of new dimensionless number is compared with the square root of Wallis parameter for the reported data [7] to observe the difference.

Experimental studies on the flooding phenomenon, closely associated churn flow regime, were carried out with air-water flow in a 0.032 m diameter for 1m and 0.3m long test section in vertical pipe with a porous wall outlet [7]. It can be mentioned that the reported experiment [5] conducted at diameter 0.032 m with test sections 0.91 m and 0.46 m while another reported experiment [6] conducted also at diameter 0.032 m with test sections 1 m and 0.5 m.

The square root of the dimensionless superficial liquid velocity and superficial gas velocity are drawn in Fig. 1 according to Wallis parameter using reported data [7]. The Wallis correlation with m=1, c=0.725 and m=1, c=1 also drawn in Fig. 1. It is clearly seen that the experimental result of Wallis correlation shows large deviation with the Wallis parameter.

From the above mentioned experimental results, the square root of the dimensionless superficial liquid velocity and superficial gas velocity are drawn in Fig. 1 according to Wallis parameter. The Wallis correlation with m=1, c=0.725 and m=1, c=1 also drawn in Fig. 1. It is clearly seen that the experimental result of Wallis correlation shows large deviation with the Wallis parameter.

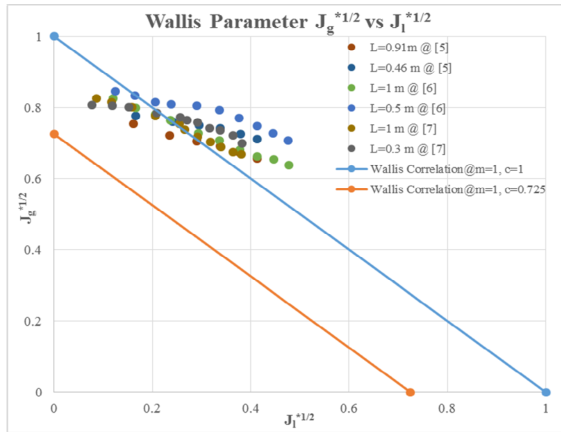

Fig. 1. Wallis parameter and correlation

The newly derived dimensionless parameter with square root is also drawn in Fig. 2 using the same reported data [7]. The comparison of dimensionless number between Wallis parameter in Fig. 1 and new parameter in Fig. 2 clearly shows the better agreement in case of new parameter than the Wallis parameter from a statistical point of view. The Fig. 1 reveals a wide scattering of data according to Wallis parameter while the Fig. 2 shows narrow range of scattered data according to new parameter. It can be mentioned that the density of liquid, viscosity of liquid, and surface tension used in this calculation were 996.8 kg/m^3, 0.00089 Kg/ms, and 0.0735 N/m respectively for air-water fluid.

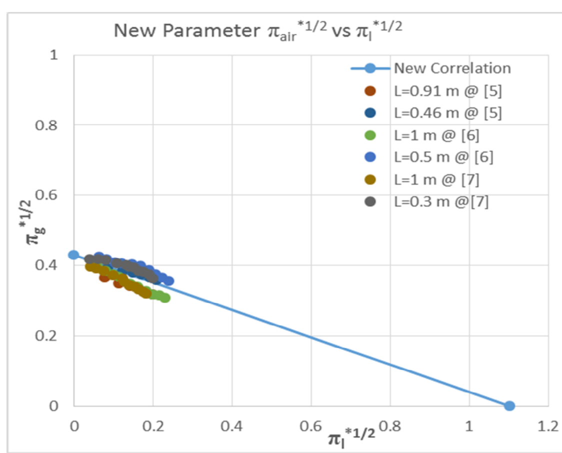

Fig. 2. New parameter and correlation

An attempt has been made to find an appropriate correlation which correlates the above mentioned experimental results, in addition, to other experimental results. On the basis of best fit graph, we can get the value of slope m=0.39 and c=0.43 according to equation (7) and the new correlation is finally written as equation (8).

$\pi_g^{*1/2} + 0.39\pi_l^{*1/2}=0.43$ ……… (8)

4. Discussions

To examine the applicability of the newly developed non dimensional parameter and correlation, another experimental results [8] are used in case of air-water CCFL in vertical tube. The experimental flooding air velocity and liquid velocity of two different diameter 0.025 m, 0.067 m with test section for each case 1.8 m and 0.5 m are available in this literature [8]. It can be mentioned that the smooth inlet and outlet condition for air-water fluid was used in this literature [8] which is different from the previous literature [5, 6, 7]**.** The Wallis parameter and correlation is shown in Fig. 3 while the Fig. 4 shows the newly developed parameter and correlation according to the experimental results [8].

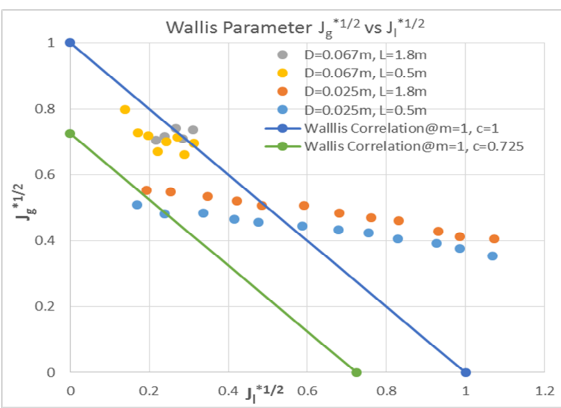

Fig. 3. Wallis parameter and correlation

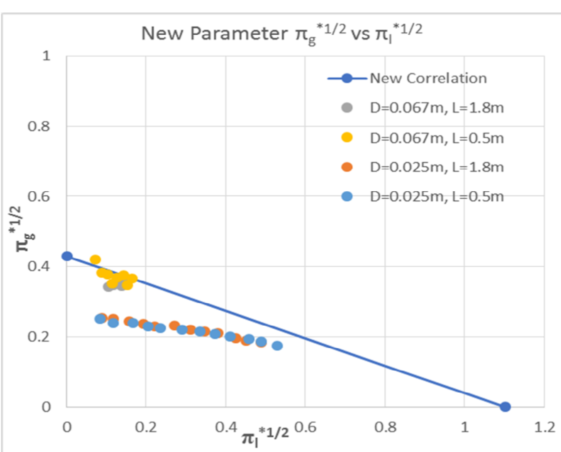

Fig. 4. New parameter and correlation

It is clearly seen according to Fig. 3 and 4 that the Wallis parameter shows wide scattering data while the new parameter shows narrow scattering which means ultimately a better agreement. It is noticeable in Fig. 4 that in case of diameter 0.025 m, the newly derived parameter shows same trend for length 1.8 m and 0.5 m respectively while Wallis parameter shows different trend.

It is clearly seen according to Fig. 4 that the new correlation shows complete over prediction in case of diameter 0.025 m and it also shows slight over prediction in case of diameter 0.067 m. The reason for this discrepancy may be due to the different inlet and outlet geometry of the test section in the previous literature [5, 6, 7] with comparison to this literature [8]. As an example, flooding experiments were carried out with air-water flow in liquid outlet of porous wall and the air pressure at the test section outlet maintained at 1.33 bar with ambient temperature [7] while the smooth inlet and outlet condition for air-water fluid used in this study [8]. The length over diameter ratio for diameter 0.025 m is 72 and 20 in case of length 1.8 m and 0.5 m, respectively. On the other hand, the length over diameter ratio for diameter 0.067 m is 26.87 and 7.46 in case of length 1.8 m and 0.5 m, respectively. This length over diameter factor can also contribute to the discrepancy. Since the new correlation contains slope and gas intercept, it is flexible to change by considering the test geometry which requires more investigation.

5. Conclusion

This study focuses on the derivation of non-dimensional parameter and correlation considering fluid properties, test section length, and diameter for air-water counter current flow in vertical pipe. The derived non-dimensional parameter is validated with the experimental results from literature. The comparison between Wallis parameter and newly developed parameter is also made and it is found that the new parameter shows better agreement from a statistical point of view, less scattered data with the comparison to the Wallis parameter. Moreover, a CCFL correlation is proposed by the best fit graph using newly developed dimensionless parameters.

The derivation of new dimensionless parameter that includes superficial velocity of fluid, density, surface tension, viscosity, gravitational acceleration, diameter, and length of the tube, is the foremost contribution in this study. Another important aspect of this study is the proposal of new correlation using new dimensionless parameter.

The proposed new parameter and correlation were validated only few experimental results which is the limitation of this study. Besides, according to new

CCFL parameter, the superficial velocity of flooding increases with the increase of length of test section which contradicts with some literatures. Care should be made to use this parameter and correlation as a generalized form because CCFL experimental conditions and purpose vary from case to case. In further study, the validation of the proposed CCFL parameter will be conducted using more experimental data and the verification will be done by implementing the proposed correlation in a system code.

Acknowledgements

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References

[1] Wallis, G.B., One-Dimensional Two-phase Flow. Mc-Graw Hill Book Company, New York, 1969.
[2] Pushkina, O. L., Sorokin, Y. L., Breakdown of Liquid Film Motion in Vertical Tubes. Heat Transfer Soviet Res. 1, 5, 1969.
[3] S. Kalliadasis, C. Ruyer-Quil, B. Scheid, M. G. Velarde, Falling Liquid Films, Springer London, 2011.
[4] Bankoff, S. G., and S. C. Lee, NUREG/CR 3060, A Critical Review of the Flooding Literature, U.S. Nuclear Regulatory Commission, 1983.
[5] Hewitt, G. F., Lacey, P. M. C. & Nicholls, B., Transitions in Film Flow in a Vertical Tube. Report AERE-R4614. Also Presented at the Symposium on Two-phase Flow, Exeter, Devon, Paper B4, 1965.
[6] Mcquillan, K. W., Flooding in Annular Two-phase Flow. Ph.D. Thesis, 1985.
[7] A. H. Govan, G. F. Hewitt, H. J. Richter, and A. Scott, Flooding and churn flow in vertical pipes, Int. J. Multiphase Flow Vol. 17, No. I, pp. 27-44, 1991.
[8] M. Vijayan, S. Jayanti, A. R. Balakrishnan, Effect of tube diameter on flooding, Int. J. Multiphase Flow 27, 797-816, 2001.