Proceedings of the Korean Nuclear Society Autumn Meeting
Taegu, Korea, October 1997

Interfacial Friction Factors for Air-Water Co-current Stratified Flow in Inclined Channels

Ki Yong CHOI and Hee Cheon NO
Korea Advanced Institute of Science and Technology

Abstract

The interfacial shear stress is experimentally investigated for co-current air-water stratified flow in inclined rectangular channels having a length of 1854mm, width of 120mm and height of 40mm at almost atmospheric pressure. Experiments are carried out in several inclinations from 0^o up to 10^o. The local film thickness and the wave height are measured at three locations, i.e., $L/H = 8, 23$, and 40. According to the inclination angle, the experimental data are categorized into two groups; nearly horizontal data group ($0^o \leq \theta \leq 0.7^o$), and inclined channel data group ($0.7^o \leq \theta \leq 10^o$). Experimental observations for nearly horizontal data group show that the flow is not fully developed due to the water level gradient and the hydraulic jump within the channel. For the inclined channel data group, a dimensionless wave height, $\Delta h/h$, is empirically correlated in terms of Re_G and h/H. A modified root-mean-square wave height is proposed to consider the effects of the interfacial and wave propagation velocities. It is found that an equivalent roughness has a linear relationship with the modified root-mean-square wave height and its relationship is independent of the inclination.

1. Introduction

A knowledge of the interfacial shear stress plays a central role in the development of improved models for two-phase flow systems. In particular, thermal-hydraulic responses of a pressurized water reactor (PWR) during a small-break-loss-of-coolant (SBLOCA) are characterized by phase separation due to gravity, including the occurrence of stratified two-phase flow in horizontal legs. The interfacial drag and the liquid holdup in these legs have a significant influence on the coolant inventory distribution in the primary system during SBLOCA transients. The interfacial drag is also a crucial parameter governing transport phenomena such as heat and mass transfer in many fields of application, including heat exchangers, reboilers, condensers, spray and bubble columns and pipelines. Usually, the analysis for horizontal (or inclined) flows is more complicated than that for vertical flows, since it can have various flow subregimes, such as smooth, 2-D wavy, 3-D wavy, and roll wavy regimes, according to the phase velocity. In particular, one of the predominant forces acting on the fluids in pipelines is gravity. Due to the large density ratio associated with gas-liquid systems, this can be of much more importance than other forces involved. Thus, a small change of inclination can cause a major change of the interfacial structure in the flow within the pipelines. Most of the experiments have been carried out in a very narrow range of inclinations near horizontal. In spite of much work, there is no literature to provide the experimental raw data for the interfacial friction factor in a wide range of inclinations. This paper presents experimental results of the studies on the interfacial friction factor for co-current air-water stratified flow in various inclined rectangular channels. The experimental work discussed in this paper aims at studying the effects of inclination angles on the interfacial friction factor. The relationship between the wave height and the interfacial friction factor is discussed based on the concept of equivalent roughness.

2. Experimental works

A two-phase flow loop is designed to be rotatable from horizontal to vertical position. The overall loop schematic is illustrated in figure 1. The air is provided to a test section from the central air supply system. Its flow rates in the range of 300 to 2800 LPM are metered by a rotameter

Table 1: Experimental conditions

Parameter	Units	Condition	Remarks
H	mm	40	channel height
W	mm	120	channel width
L	mm	1854	channel length
θ	degree	$0 \sim 10$	inclination angle
j_L	m/s	0.04,0.07,0.09,0.12	liquid superficial velocity
j_G	m/s	$0 \sim 9.6$	gas superficial velocity

made by Dwyer Co.. The water is supplied from a water supply tank to the test section by a DC pump, drained to a sump tank, and pumped to the water supply tank. The water flow rates are measured by a vortex flowmeter in the range of 0 to 25GPM. A transparent tube, which is filled with water, is used to measure the inclination angle with an accuracy of 0.04 degree. The pressure drop along the test section is measured by a micro-manometer which has 2mm or 20mm H_2O in its full scale. All the experiments are performed at almost atmospheric pressure and at room temperature. The experimental conditions are listed in table 1. The rectangular channel, having a length of 1854mm, width of 120mm, and height of 40mm, is used as a test section. In order to measure the instantaneous liquid film thickness within the test section, electrical wire-wire probes are used. Each wire-wire probe consists of two parallel nickel wires 0.2mm in diameter and with a separation distance of 2.4mm. The wires are kept in slight tension to avoid the noise signal due to vibration of the wires. Three pairs of wire-wire probes are installed at each flange which is located about $L/H = 8, 23$ and 40, apart from the liquid entrance. Calibration is performed by using two needle tips with digital micrometers with an accuracy of 0.01mm. The mean liquid film thickness is obtained by averaging the mean liquid film thicknesses measured at different locations within the test section. Assuming the interfacial waves to be approximately sinusoidal, the wave height is obtained from the root mean square wave height. The interfacial shear stress is calculated by gas phase momentum balance. If the momentum change of the air along the flow direction is negligible, the interfacial shear stress in the rectangular channel is expressed from the following force balance:

$$\tau_i = (H-h)\frac{\Delta P}{L} - \frac{W+2(H-h)}{W}\tau_{wG} + (H-h)\rho_G g \sin\theta, \qquad (1)$$

where H and W are the height and the width of the channel, respectively, L is the distance between the pressure taps, h is the mean liquid film thickness, τ_{wG} is the air-to-wall shear stress, and θ is the inclination angle (positive angles indicate downflow). The Blasius type correlation is used for the evaluation of the air-to-wall shear stress. The interfacial friction can be defined based on the relative velocity between the gas phase velocity u_G and the interfacial liquid velocity u_i. In general, the reliable measurement or calculation for u_i is difficult, which makes the practical application more difficult. Thus, the interfacial friction factor f_i is defined only by the gas phase velocity, u_G, throughout this paper.

3. Results and Discussions

3.1 Data classification

The present test range of the flow rates of both phases is limited to the stratified flow. In no cases annular or intermittent flows are reached, even if some liquid entrainment by the gas flow is observed at high gas velocity. The stratified smooth regime is not observed when the channel is slightly downwardly inclined. Visual observations show that inclination angle considerably affects the mean liquid film thickness. When the inclination angle is very close to horizontal, the interfacial water level gradient, decreasing from the entrance to the exit of the liquid flow, is observed. The water level gradient becomes mild and a hydraulic jump is created near the entrance of the liquid flow with an increase in the gas velocity. A further increase of the gas flow rates pushes the hydraulic jump toward the exit of the liquid flow. At higher gas flow rates, the hydraulic jump escapes the test section and the adverse interfacial water level gradient, increasing from the entrance to the exit of the liquid flow, is observed. The formation of the hydraulic jump makes both the super-critical and the sub-critical regions coexist within the test section. It seems that the wave structures and/or growth rates are varied depending on whether the flow is sub-critical or not. Interfacial waves grow propagating in the super-critical region in front of the hydraulic jump, but decay out passing through the hydraulic jump. The waves then restart to grow in the sub-critical region. Therefore, the assumption of the uniform pressure gradient within the test section is no more valid, due to the water level gradient and the hydraulic jump. Such non-uniform flow in the stratified flow was also investigated by Bishop et al.(1986). On the other hand, for an inclination angle greater than about 0.7 degree, such non-uniform flow is not observed. Due to downward gravity force, the liquid rapidly flows and has a lower level within the channel in the condition of super-critical flow. Therefore, the liquid flow is easily fully developed and the assumption of the uniform pressure gradient within the test section is valid.

Based on the present experimental observations, the data can be roughly categorized into two groups according to the inclination angle.

- Nearly horizontal channel($0^o \leq \theta \leq 0.7^o$), in which the stratified air-water flow is not fully developed. As the water level gradient and the hydraulic jump exist, it is hard to define the wavy parameters such as the mean film thickness and the wave height.
- Inclined channel($0.7^o \leq \theta \leq 10^o$), in which the assumption of the fully developed air-water stratified flow is valid. The hydraulic jump is never observed and the water always flows down in the super-critical condition. The effect of the water level gradient can be negligible so that the wave parameters can be easily extracted through the experimentation.

3.2 Prediction of the mean liquid film thickness

Figure 2 compares the measured mean liquid film thickness with the predictive model by Taitel and Dukler(1976) for the horizontal flow. The predictive model by Taitel and Dukler(1976) is modified to consider the rectangular geometry as follows:

$$\chi^2 f(\alpha_L, n, r) - f(\alpha_L, m, r, \frac{f_i}{f_G}) - 4Y = 0, \tag{2}$$

where f is a functional relationship involving the parameters within the brackets; n and m are the exponents of the Reynolds number in the friction factors of liquid and gas phases respectively, α_L is the liquid fraction, χ is the Lockhart-Martinelli parameter, Y is the dimensionless parameter considering inclination, and r is the aspect ratio of the rectangular channel. For each liquid flow rate, experimental holdup h/H is substantially lower than the predicted value at the higher χ. As χ decreases, h/H does not significantly decrease for large χ, compared with the decreasing of the predicted value. Eventually, the measured liquid holdups merge to the predicted χ_{tt} line. This behavior can be explained based on the observation that initially increased gas flow rate acts primarily to depress the water level gradient rather than to reduce the average liquid holdup. This finding was also discussed by Akai et al.(1980) and Bishop et al. (1986).

Whereas, the liquid fraction is not uniquely determined by χ in inclined channels, where the dimensionless parameter considering the inclination, Y should be also considered. Figure 3 shows the comparison of the experimental liquid holdup with the predictive value for the inclination angle greater than 0 degree. The predictions by the Taitel and Dukler's model are generally lower than the experimental values. The deviation from the predictive value is large for the high liquid holdup. The predictive values are well consistent with the experimental one for the lower liquid holdup.

3.3 Prediction of the Wave height

In the stratified wavy flow, the wave height plays a role of the roughness element making a significant resistance to motion in the turbulent gas flow. Many studies on the equivalence between the roughness on the solid surface and liquid wave have been undertaken by Cohen et al.(1968), Kordyban(1974), Andreussi et al.(1987), Kowalski(1987), Andritsos(1986), Andritsos et al.(1987), Fukano(1985). For the inclined data group, the correlation for the wave height with respect to the dimensionless macroscopic parameters is developed. The wave height is assumed to be a function of the liquid Reynolds number and gas Reynolds number, the mean film thickness and the inclination angle. The parameters Re_L, Re_G, h, and θ are not independent with each other. Among them, only 3 parameters are independent of each other. Thus, it can be inferred that the wave height is a function of the liquid Reynolds number, gas Reynolds number, and the mean film thickness. Regression study on the experimental data shows that the dependency on the liquid Reynolds number is small enough to be neglected. The final correlation for the dimensionless wave height is obtained

$$\frac{\Delta h}{h} = 2.49 \times 10^{-6} Re_G^{0.84} (\frac{h}{H})^{-0.83}. \tag{3}$$

The comparison with the experimental data is shown in figure 4. The agreement is very good.

3.4 Prediction of the interfacial friction factor

On the whole, f_i/f_G is proportional to the gas superficial velocity in inclined channels with $0.7^o \leq \theta \leq 10^o$. The conventional region of the constant f_i/f_G is not seen. It is attributed to the facts that the stratified smooth regime is not observed in inclined channels due to the gravity force. As the inclination angle increases, the slope with respect to j_G becomes mild. For a fixed j_G and an inclination angle, the liquid flow rates also affect f_i/f_G, but it appears not to be so large. The influence of the inclination angle on f_i/f_G is more dominant than that of j_L. The increasing trend of f_i/f_G with j_G is similar to that of Δh, implying that the interfacial friction factor can be modeled by the concept of equivalent roughness. The equivalent roughness can be calculated from the results of Karman and Nikuradse's studies for completely rough regimes:

$$\frac{1}{\sqrt{4f_i}} = 2.04 \log \frac{a}{k_s} + 1.74, \tag{4}$$

where k_s is the equivalent roughness and a is the distance from the interface to the location of the maximum gas velocity. Cohen(1968) suggested that the equivalent roughness k_s equals to $3\sqrt{2}$ times root-mean-square wave height for $\Delta h^+ \geq 12$ in the horizontal stratified flow, that is,

$$k_s^+ = 3\sqrt{2}\Delta h^+, \tag{5}$$

where the dimensionless wave height $\Delta h^+ = \Delta h u^*/\nu_G$ and the equivalent roughness $k_s^+ = k_s u^*/\nu_G$ are nondimensionalized by using the interfacial friction velocity u^*. However, the present results show that the dimensionless equivalent roughness k_s^+ is poorly correlated with the dimensionless wave height Δh^+, as seen in figure 5. The slopes are different with respect to the liquid superficial velocities. Data for higher liquid superficial velocities have milder slopes than those for lower liquid superficial velocities.. It indicates that the interfacial friction factor in stratified wavy flow cannot be directly treated by means of the equivalent roughness without considering the effects of the liquid velocity. Phenomenologically, an increase in the liquid superficial velocities makes the mean film thickness thicker. The thicker liquid film results in decreasing the hydraulic diameter of the gas phase and thus increasing the frictional drag. Furthermore, it is relatively easy for the wave height to grow on the thick liquid film rather than on the thin liquid film. On the other hand, an increase in the liquid superficial velocity causes the interfacial liquid velocity and wave propagation velocity to increase. As a result, it leads to a decrease in the interfacial frictional drag. A new dimensionless parameter is needed to describe the relationship between k_s and Δh, rather than Eq.(5). A modified dimensionless parameter considering the interfacial liquid and wave velocities is proposed as follows:

$$\Delta h^* = \frac{\Delta h u^*}{\nu_G} \frac{1}{Re_L}, \tag{6}$$

where Re_L is the liquid Reynolds number defined by $Re_L = hu_L/\nu_L$. A best fit curve between k_s^+ and Δh^* is found using a least square method as follows:

$$k_s^+ = 8008\Delta h^{*0.98}. \tag{7}$$

The results using the modified dimensionless wave height are plotted in figure 6. The scattering due to the changes of j_L is reduced and the data merge to a constant line. As can be seen in Eq.(7), the exponent of Δh^* is so close to unity that the relationship between k_s^+ and Δh^* can be considered to be almost linear. The interesting results are that the effect of the inclination angle disappears when the modified dimensionless wave height Δh^* is used as an equivalent roughness. When Eq.(7) is used as an equivalent roughness in inclined channels, the interfacial friction factor can be implicitly calculated from Eqs.(3) and (4). However, an empirical correlation of the interfacial friction factor is needed for practical application. It can be postulated that the interfacial friction factor is a function of both the gas and liquid Reynolds numbers and the liquid holdup for inclined channels. Thus, an attempt was made to correlate the friction factor in the form of the power-law relationship:

$$\frac{f_i}{f_G} = 1 + 0.006(\frac{h}{H})^{0.72} Re_G^{1.56} Re_L^{-1.16}, \tag{8}$$

for

$$\begin{aligned} 0.054 \leq h/H &\leq 0.264 \quad , \\ 1517 \leq Re_L &\leq 4745 \quad , \\ 3960 \leq Re_G &\leq 37670 \quad , \end{aligned}$$

where $Re_G = u_G D_G/\nu_G$.

4. Conclusions

According to the inclination angle, the experimental data are categorized into two groups: nearly horizontal data group ($0^\circ \leq \theta \leq 0.7^\circ$), and inclined channel data group ($0.7^\circ \leq \theta \leq 10^\circ$). The water flow is not uniform in nearly horizontal data group due to the water level gradient and the hydraulic jump. Such non-uniform phenomena in nearly horizontal inclinations result in the large scattering of the interfacial friction factors. Whereas, the contribution of the water level gradient and the hydraulic jump to the pressure drop cannot be ignored in inclined channels. The relationship between Δh^* and k_s^+ is almost linear and the relationship is independent of the inclination and the water flow rates. Therefore, the interfacial friction factor can be predicted by the relationship between Δh^* and k_s^+ and the empirical correlation for $\Delta h/h$.

References

[1] Bishop, A.A. et al. 1986 *Int. J. Multiphase Flow*, **12**, p957-975.
[2] Taitel, Y. and Dukler, A.E. 1976 *AIChE. J.*, **22**, 47-55.
[3] Akai, M. et al. 1980 *Int. J. Multiphase Flow*, **6**, 173-190.
[4] Cohen, L.S. and Hanratty, T.J. 1968 *J. Fluid Mech.* **31** 467-479.
[5] Kordyban, E. 1974 *Trans. ASME J. Fluid Eng.* 97-102.
[6] Andreussi, P. and Persen, L.N. 1987 *Int. J. Multiphase Flow* **13** 565–575.
[7] Kowalski, J.E. 1987 *AIChE J.* **33** 274–281.
[8] Andritsos, N. 1986 *Ph.D. Thesis, Chem. Eng., Univ. of Illinois at Urbana-Champaign.*
[9] Andritsos, N. and Hanratty, T.J. 1987 *AIChE J.* **33** 444–454.
[10] Fukano, T. et al. 1985 (5th report). *Tran.JSME* **51**, 494-502.

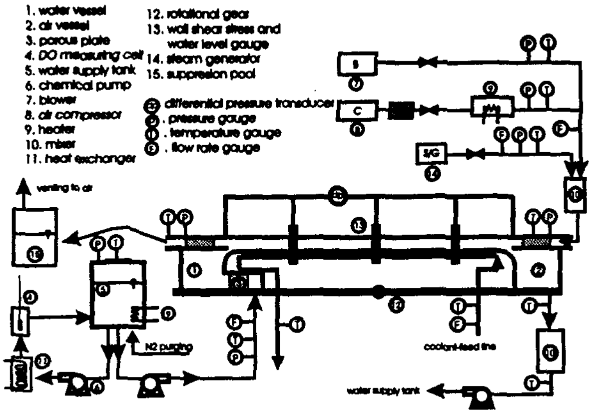

Figure 1 Schematic diagram of the experimental rig

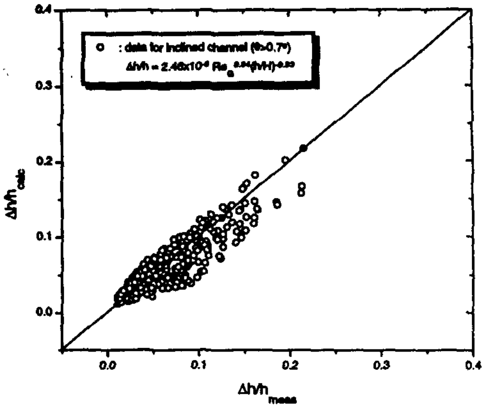

Figure 4 Comparison of the correlation for the dimensionless wave height with data

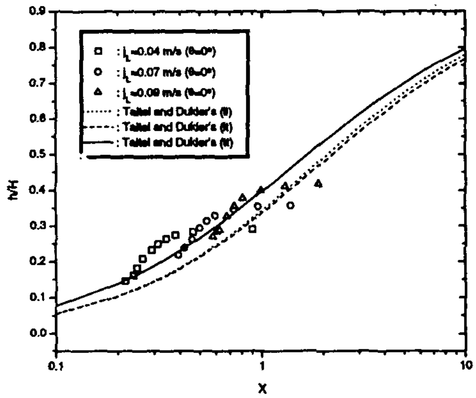

Figure 2 Comparison of the mean film thickness with Taitel and Dukler's prediction in horizontal flow

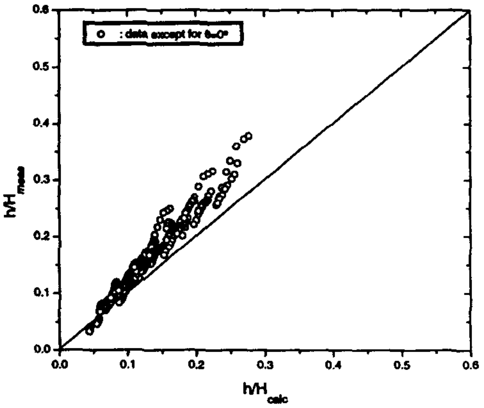

Figure 3 Comparison of the mean film thickness with Taitel and Dukler's prediction in inclined flow

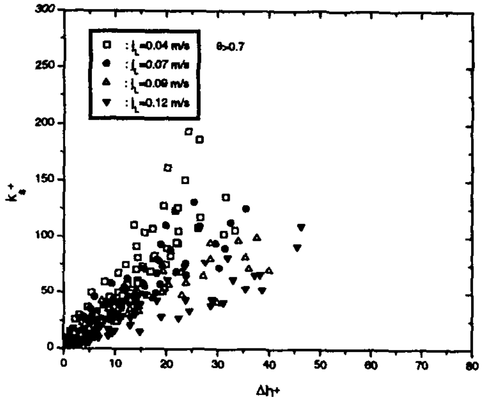

Figure 5 Relationship between an equivalent roughness and rms wave height

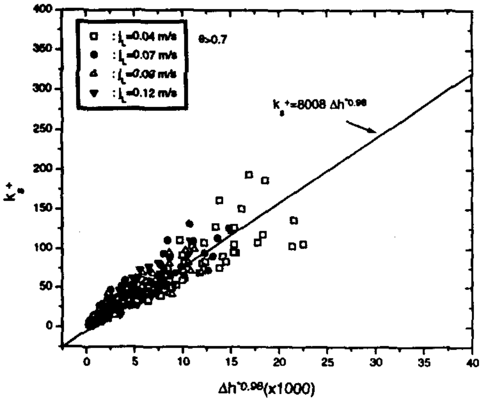

Figure 6 Relationship between an equivalent roughness and modified rms wave height