532.529

Paper No. 152-15

On Ripple of Annular Two-Phase Flow —

2. Characteristics of Wave and Interfacial Friction Factor*

By Kotohiko SEKOGUCHI**, Keiichi HORI***
 Masao NAKAZATOMI[†], Kaneyasu NISHIKAWA**

Several empirical equations have been proposed of the interfacial friction factor in a gas-liquid two-phase annular flow, but there exists a significant inconsistency among the results calculated by these correlations. In addition, none of them indicated good agreement with the present experimental values obtained in ripple flow regime.

An experiment was made to collect the information on main parameters characterizing air-water interface, such as wave height, wave propagation velocity and wave frequency, possibly interrelated with the interfacial friction factor. Using the results, there of a new relationship between the interfacial friction factor and the parameters was introduced.

1. Introduction

The accurate evaluation of interfacial shear stress or interfacial friction factor is very significant for solving the momentum equation for gas-liquid annular flow. An examination of the major existing correlations of interfacial friction factor indicates that they are no longer in good agreement with each other. The purpose of this study is to understand more detailed characteristics of gas-liquid interface in the ripple regime of upward air-water annular flow. Since the wave height of ripple is low, the liquid film is often regarded for this regime as uniform in thickness. The interface covered with ripples is evidently more smooth to the eyes than that accompanied with disturbance waves. However, it seems reasonable to suppose that ripples play an important role in the momentum transfer, because the interfacial friction factor is highly raised.

A mathematical model to relate the wave shape with the radial distributions of wave frequency and holdup (relative contact time with liquid phase) was introduced in a previous report⁽¹⁾. In this report, the characteristics of interface are discussed based on the experimental results of various parameters such as mean liquid film thickness, maximum and minimum liquid film thicknesses, maximum wave height, mean wave height, wave frequency and wave velocity in ripple regime. Further the experimental data on interfacial friction factor are also demonstrated, and a functional relationship between interfacial friction factor and major parameters (wave height, probability density distribution of wave heights, wave frequency and wave velocity)

characterizing the gas-liquid interface is introduced on the mathematical model employed in the previous report.

2. Nomenclature

C : dimensionless constant in Eq.(20) = $8C'/C''$
 C' : dimensionless coefficient depending only on tube internal diameter in Eq.(15)
 C'' : dimensionless coefficient depending only on tube internal diameter in Eq.(19)
 D : tube internal diameter
 F : interfacial shear force
 F_v : interfacial shear force to smooth interface
 F_D : additional interfacial shear force due to roughness of interface
 H : wave height
 $\bar{H}$: mean wave height
 H₀ : maximum wave height
 N_{rmax} : maximum wave frequency
 N_{rt} : total number of ripples passing through tube cross section per unit time
 R : tube internal radius
 R_i : gas core radius $\equiv R - t_{fm}$
 Reg : gas phase Reynolds number $\equiv u_{gm} \cdot D / \nu_g$
 Reg₀ : superficial gas phase Reynolds number $\equiv u_{g0} \cdot D / \nu_g$
 Re_{l0} : superficial liquid phase Reynolds number $\equiv u_{l0} \cdot D / \nu$
 t_{fm} : mean film thickness
 t_{fmax} : maximum film thickness
 t_{fmin} : minimum film thickness
 u_i : velocity at interface
 u_r : velocity of propagation of ripples
 u_{g0} : superficial gas velocity
 u_{l0} : superficial liquid velocity
 u_{gm} : mean gas velocity
 Y_c : radial distance between wave crest and position where wave frequency is maximum
 Y_{co} : Y_c for wave with maximum wave height
 $\bar{Y}_c$: mean value Y_c in Eq.(3)
 y : radial distance from tube inner wall
 Y_{η=0.35} : radial distance between tube inner wall and location where relative contact time is 0.35
 dP/dZ : pressure gradient
 α : void fraction
 η : relative contact time with liquid phase
 λ_i : interfacial friction factor

* Received 6th Feb., 1976.

** Professor, Faculty of Engineering, Kyushu Univ., Hakozaki, Higashi-ku, Fukuoka, 812.

*** Engineer, Takasago Technical Institute, Mitsubishi Heavy Industry.

† Professor, Ube Technical College.

- λ_{iv} : friction factor defined by Eq.(13)
 λ_{iD} : friction factor defined by Eq.(14)
 ρ_g : gas density
 σ : standard deviation in Eq.(3)
 τ_i : interfacial shear stress
 τ_{iv} : shear stress defined by Eq.(10)
 τ_{iD} : shear stress defined by Eq.(11)
 ψ : probability density distribution function of Y_c by Eq.(3)

3. Experimental apparatus and procedure

A schematic diagram of the experimental apparatus used in this study is shown in Fig. 1. The details of the apparatus are described in previous report⁽¹⁾. The test tubes vertically set were made of acrylic resin and had inner diameters of 13.0, 19.8, 25.0 and 26.1 mm.

The pressure taps P3, P4 and P5 were used for measuring the pressure gradient. The electric probe device, EP, was located about 7 m downstream from the air-water mixer, M, (porous sinter injector) to measure the parameters on film flow such as relative contact time, film thickness, wave frequency and wave velocity. This electric probe device was composed of two types of electric conductance probes as shown in Fig.2; one consisted of a radially traversable needle tip electrode, E2, (platinum wire of 0.3 mm diameter) and a fixed electrode, E1, (nickel wire of 1 mm diameter) flush with the tube

Fig.1 Schematic diagram of experimental apparatus

inner surface; and the others, E3 and E4, respectively consisted of a pair of fixed electrodes (nickel wires of 1 mm diameter) flush with the tube inner surface. The traversable conductance probe, the first type, was used for the measurement of relative contact time and wave frequency at an arbitrary distance from tube inner surface. The fixed conductance probes, the second type, were for the measurement of wave velocity. Figure 2 also shows the connections of the conductance probes and the measuring equipment. An example of a pair of signals on the oscilloscope screen derived from the fixed conductance probes, E3 and E4, is shown in Fig.3. The phase shift of two corresponding waves and the distance between

- DC: Digital counter-timer-frequency-ratio meter
 E1: Fixed electrode
 E2: Needle electrode } Traversable probe
 E3, E4: Fixed electrodes-Fixed probe
 e1-e3: Dry batteries
 R1-R3: Electric resistances
 MH: Micrometer
 Os: Oscilloscope
 S: Spring

Fig.2 Electrical measuring devices and circuit connections

$D=13.0$ mm, $u_{go}=14.0$ m/s, $u_{zo}=0.003$ m/s
 Distance between probes, E4 and E3 : 3 mm

Fig.3 Typical example of oscilloscope record reading of time interval gives wave velocity

two probes give the wave velocity. The measurement of wave velocity was made with the test tubes of 13.0 and 25.0 mm in diameter.

The flow conditions tested cover the following ranges. Air and water flow rates were chosen for the flow pattern to be in the ripple regime.

Pressure: 1.06-1.19 ata. Temperature: 10-30 °C. Superficial velocity and superficial Reynolds number for air: $u_{go} = 15-60$ m/s, $Re_{go} = 15000-80000$. Superficial velocity and superficial Reynolds number for water: $u_{go} = 0.003-0.008$ m/s, $Re_{go} = 35-200$.

4. Experimental results and discussion

4.1 Characteristics of gas-liquid interface

4.1.1 Mean liquid film thickness

The gas-liquid interface of liquid annulus in ripple regime is not smooth, still mean film thickness may be a principal parameter or index to the analytical treatment of the film flow. For this reason the experimental data are first presented on mean film thickness, t_{fm} , which is determined by

$$t_{fm} = R - \sqrt{R^2 - 2 \int_0^R \eta(r) r dr} \quad (1)$$

where $\eta(r)$ is the relative contact time.

Figure 4 shows examples of mean film thickness marked by a symbol X on the curves of η against the distance, y , from inner tube wall. It can be recognized that mean film thickness is closely related with the distance corresponding to $\eta=0.35$. Figure 5 reveals the existence of the same correspondence between t_{fm} and $y_{\eta=0.35}$ for another test data.

Fig.4 Typical results of relative contact time, η , against distance from wall, y

This fact suggests that taking the value of $y_{\eta=0.35}$ as mean film thickness is simple in determination and is effective for a rather wide range of film thicknesses.

Figure 6 indicates the effect of superficial gas Reynolds number on relative mean film thickness, t_{fm}/R . The value of t_{fm}/R is nearly constant for the region of $Re_{go} < 30000$, but decreases with Re_{go} for $Re_{go} > 30000$. Although the effect of water flow rate taken as a parameter in the figure is a little, t_{fm}/R definitely increases with water flow rate. The maximum value of t_{fm} for the ripple regime tested was about 0.3 mm.

4.1.2 Maximum and minimum liquid film thicknesses

Figure 7 gives the results for both the maximum and minimum film thicknesses, which are determined from the η vs. y curves, i.e., maximum film thickness or maximum height of crest is equal to the value of y for $\eta=0$ and minimum film thickness is equal to the value of y for $\eta=1$. Maximum film thickness tends to decrease with u_{go} and increase with u_{to} . Its greatest value can reach at about 1 mm, which is three or more times the mean film thickness. The change in minimum film thickness is not so systematic with flow rates as in maximum film thickness, but it roughly decreases with u_{go} . Its order of magnitude is 0.01 mm to 0.1 mm.

4.1.3 Maximum wave height

Maximum wave height, H_o , is defined as the difference between maximum and minimum film thicknesses. Figure 8 gives the results for maximum wave height, which shows an abrupt decrease with u_{go} and an increase with u_{to} . Maximum wave height also becomes about three times as large as mean film thickness, and is greater than the thickness of gas phase laminar sublayer (say, 0.04 mm for $u_{go}=20$ m/s). The existence of such ripples with high crest must give an evidence that interfacial friction factor highly exceeds that of smooth tube.

4.1.4 Mean wave height

Mean wave height, $\bar{H}$, is determined based

Fig.5 Comparison between mean film thickness, t_{fm} , and distance from tube inner wall to location where $\eta=0.35$, $y_{\eta=0.35}$

on the mathematical model introduced in previous report⁽¹⁾ as

$$\bar{H} = \int_0^{Y_{co}} H\psi(Y_c) dY_c = \frac{H_0}{Y_{co}} \int_0^{Y_{co}} Y_c \psi(Y_c) dY_c \quad (2)$$

where

$$\psi(Y_c) = \frac{1}{\sqrt{2\pi} Y_c \sigma} \exp\left\{-\frac{1}{2}\left(\frac{\ln Y_c - \ln \bar{Y}_c}{\sigma}\right)^2\right\} \quad (3)$$

Figure 9 shows the mean wave height, calculated by the above equations. The tendency of $\bar{H}$ against u_{go} is very similar to H_0 , but its magnitude is one fifth of H_0 or less. Figure 10 shows the relation between mean wave height and mean film thickness. Mean wave height increases in proportion nearly to the square of mean film thickness. Further, it can be considered from Figs. 8 to 10 that liquid film has the ripples, heights of which are comparable to the mean film thickness.

4.1.5 Maximum wave frequency

Maximum wave frequency, N_{rmax} , is plotted against superficial gas velocity and mean

Fig. 6 Relative mean film thickness, t_{fm}/R , vs. superficial gas phase Reynolds number, Re_{go}

Fig. 7 Maximum film thickness, t_{fmmax} , and minimum film thickness, t_{fmmin} , vs. superficial gas velocity, u_{go}

film thickness in Figs. 11 and 12 respectively. The maximum wave frequency obtained from the test of a tube of 13.0 mm diameter increases with u_{go} in the region of $u_{go} < 40$ m/s and decreases with further increase of u_{go} . However, this tendency was not observed with the tubes of 19.8 mm and 26.1 mm in diameter, and maximum wave frequency monotonously increases with u_{go} . Except for both the suspending wave and transition regimes (air velocities less than 20 m/s), the maximum wave frequency increases with a decrease of tube diameter. The order of magnitude measured for maximum wave frequency is from 100 1/s to 1000 1/s.

Maximum wave frequency rapidly decreases with an increase of mean film thickness as seen in Fig. 12. The comparison of Fig. 10 with Fig. 12 leads to a conclusion that as liquid film becomes thicker, the wave height increases but the wave frequency decreases; thus, the thinner the liquid film is, the greater wave frequency occurs.

4.1.6 Propagation velocity of ripple

The values of wave velocity, u_r , measured with the test tubes of 13.0 or 25.0 mm in diameter are shown in Fig. 13. Wave velocity increases with $u_{go}^{1.5}$, and is below 2 m/s and less than that of disturbance wave, which is 2 to 5 m/s⁽²⁾. These values of wave velocity are estimated to be from twice to four times the mean film velocity, which increases from 0.1 m/s to 0.4 m/s with an increasing u_{go} .

4.2 Interfacial friction factor

As the entrainment flow rate is negligible under the flow conditions of this study, void fraction, α , is equal to $(R_i/R)^2$. The momentum balance in gas core gives a relation between shear stress, τ_i , at interface and pressure gradient as follows:

Fig. 8 Maximum wave height, H_0 , vs. superficial gas velocity, u_{go}

$$\tau_i = \frac{R}{2\sqrt{\alpha}} \left(-\frac{dp}{dz} \right) = \frac{R_i}{2} \left(-\frac{dp}{dz} \right) \quad (4)$$

Interfacial friction factor is defined by

$$\lambda_i = \frac{8\tau_i}{\rho_g (u_{gm} - u_i)^2} \quad (5)$$

Substituting τ_i in Eq.(4) into Eq.(5) yields

$$\lambda_i = \frac{4R_i (-dp/dz)}{\rho_g (u_{gm} - u_i)^2} \quad (6)$$

Velocity, u_i , at interface is much lower than mean gas velocity, u_{gm} , so that interfacial friction factor is determined by

$$\lambda_i = \frac{4R_i (-dp/dz)}{\rho_g u_{gm}^2} \quad (7)$$

where R_i is taken as $(R - t_{fm})$.

The experimental results of interfacial friction factor obtained from Eq.(7) are plotted against Re_{go} in Fig.14, which also indicates the correlations proposed by Wallis⁽³⁾ and Robert et al.⁽⁴⁾. The chain line in the figure is drawn by the correlation of Wallis and the broken line of Robert et al., both of which are calculated using the experimental values of t_{fm} for the flow conditions $D=19.8$ mm and $u_{go}=0.003$ m/s. Further for reference, the friction factor to smooth tube is shown by a solid line calculated from Blasius'

Fig.9 Mean wave height, $\bar{H}$, vs. superficial gas velocity, u_{go}

Fig.11 Maximum wave frequency, N_{max} , vs. superficial gas velocity, u_{go}

Fig.10 Comparison between mean wave height, $\bar{H}$, and mean film thickness, t_{fm}

Fig.12 Relation between maximum wave frequency, N_{max} , and mean film thickness, t_{fm}

formula. Each formula is as follows:

Wallis: $\lambda_i = \lambda_g \{1 + 360(t_{fm}/D)\}$
 Robert et al.: $\lambda_i = \lambda_g + 1.5\{(t_{fm}/D) - (5/Re_{go})\sqrt{8/\lambda_g}\}$
 Blasius: $\lambda_g = 0.3164Re_g^{-0.25} = \lambda_i$

Interfacial friction factor decreases with Re_{go} and increases with u_{go} . The effect of D on λ_i becomes pronounced as Re_{go} decreases, and λ_i increases with D . It is found that the experimental values have poor agreement with those calculated by the above correlations.

Next, interfacial friction factor is plotted against relative mean film thickness in Fig.15. λ_i increases more steeply with an increase of t_{fm}/R . As pointed out in Section 4.1.4, wave height increases with film thickness. Therefore, it can be imagined without difficulty that the wave height is to the interfacial friction factor what the roughness is to the friction factor for rough pipe.

In Fig.15 the solid line is drawn using another Wallis' correlation⁽⁵⁾; the broken line is given by Moeck⁽⁶⁾; and the chain line by Schlichting⁽⁷⁾ as follows:

Wallis: $\lambda_i = 0.02\{1 + 150(t_{fm}/R)\}$
 Moeck: $\lambda_i = 0.02\{1 + 545(t_{fm}/R)^{1.42}\}$
 Schlichting: $\lambda_i = 4\{4 \log(R/t_{fm}) + 3.48\}^{-2}$

The formulas by Wallis and Moeck were introduced based on the experiments mainly pertaining to disturbance wave regime, so that the accuracy seems to be poor to ripple regime. The formula by Schlichting which is applicable to single-phase flow in rough pipe also gives poor prediction.

The relation between λ_i and the relative roughness of interface defined as $\bar{H}/(R-t_{fm})$ is shown in Fig.16. The value of λ_i obviously depends on the relative roughness,

Fig.13 Wave propagation velocity, u_r , vs. superficial gas velocity, u_{go}

especially in the region of $\bar{H}/(R-t_{fm}) > 0.005$ it remarkably increases with the roughness. Nikuradse's formula⁽⁸⁾ for rough pipe gives the solid line in Fig.16, which lies lower than the data points and its increasing rate to relative roughness is considerably lower. This implies that rippling surface is not simply replaced with solid rough surface in its hydraulic effect of roughness; i.e., interfacial friction factor depends not only upon the relative roughness, but also upon other parameters of interface such as wave frequency, wave propagation velocity and wave shape.

5. Relationship between λ_i and principal parameters of interface

Interfacial shear force, F , is assumed to be given as the resultant of two elements, one of which is shear force, F_v , caused by smooth solid surface and the other is additional shear force, F_D , due to the existence of ripples. That is,

$$F = F_v + F_D \quad (8)$$

which is expressed on shear stress as

$$\tau_i = \tau_{iv} + \tau_{iD} \quad (9)$$

where

$$\tau_{iv} = F_v / (2\pi R_i) \quad (10)$$

$$\tau_{iD} = F_D / (2\pi R_i) \quad (11)$$

Equations (5), (9), (10) and (11) yield

$$\lambda_i = \lambda_{iv} + \lambda_{iD} \quad (12)$$

where

$$\lambda_{iv} = \frac{4F_v}{\pi R_i \rho_g (u_{gm} - u_i)^2} \quad (13)$$

$$\lambda_{iD} = \frac{4F_D}{\pi R_i \rho_g (u_{gm} - u_i)^2} \quad (14)$$

Robert: $\lambda_i = \lambda_g + 1.5\{(t_{fm}/2R) - (5/Re_{go})\sqrt{8/\lambda_g}\}$
 Wallis: $\lambda_i = \lambda_g \{1 + 360(t_{fm}/2R)\}$
 Blasius: $\lambda_i = \lambda_g = 0.3164Re_g^{-0.25}$

Fig.14 Interfacial friction factor, λ_i , vs. superficial gas phase Reynolds number, Re_{go}

If additional shear force is a drag force acting on ripples, F_D can be given by

$$F_D = C' 2\pi R_i \rho_g (u_{gm} - u_i)^2 \times \int_0^{Y_{co}} H \frac{N_{rt}}{u_r} \psi(Y_c) dY_c \quad (15)$$

The term, $H(N_{rt}/u_r)\psi(Y_c)dY_c$, represents the product of wave height and number of waves

per unit length in the direction of flow. Equation (15) is rearranged using mean wave height, $\bar{H}$, defined in Eq.(2) as

$$F_D = C' 2\pi R_i \bar{H} \frac{N_{rt}}{u_r} \rho_g (u_{gm} - u_i)^2 \quad (16)$$

Substituting Eq.(16) into Eq.(14) gives

$$\lambda_{iD} = 8C' \bar{H} \frac{N_{rt}}{u_r} \quad (17)$$

The experimental results suggest that the dimensionless coefficient, C' , in Eqs.(15) to (17) depends on tube diameter. From the results of Fig.13 the following relation between u_r and u_{go} can be derived.

$$\begin{aligned} \text{Wallis: } \lambda_i &= 0.02\{1 + 150(t_{fm}/R)\} \\ \text{Moeck: } \lambda_i &= 0.02\{1 + 545(t_{fm}/R)^{1.42}\} \\ \text{Schlichting: } \lambda_i &= 4\{4\log(R/t_{fm}) + 3.48\}^{-2} \end{aligned}$$

Fig. 15 Interfacial friction factor, λ_i , vs. relative mean film thickness, t_{fm}/R

$$\text{Nikuradse: } 1/\sqrt{\lambda_i} = 2\log\{(R - t_{fm})/\bar{H}\} + 1.74$$

Fig.16 Interfacial friction factor, λ_i , vs. relative roughness, $\bar{H}/(R - t_{fm})$

Fig.17 Relation between interfacial friction factor due to roughness of interface, λ_{iD} , and $\bar{H} N_{rt} / (u_{go} Re_{go}^{0.5})$ to determine dimensionless constant, C , in Eq.(20)

Fig.18 Comparison between calculated value, $(\lambda_i)_{cal}$, and experimental value, $(\lambda_i)_{exp}$, on interfacial friction factor

$$u_r \propto u_{go}^{1.5} \quad (18)$$

Wave propagation velocity must be related to various parameters concerning both the liquid film and gas core, but at present definite information is lacking on this point. Therefore, for convenience Eq.(19) is rearranged to a dimensionless form as follows

$$\frac{u_r}{u_{go}} = C'' Re_{go}^{0.5} \quad (19)$$

where dimensionless coefficient C'' also is a function of D . Substituting u_r in Eq.(19) into Eq.(17) gives

$$\lambda_{iD} = C \frac{\bar{H} N_{rt}}{u_{go} Re_{go}^{0.5}} \quad (20)$$

where $C=8C''/C'$. According to the analytical model introduced in previous report⁽¹⁾, the total number of ripples passing through the tube cross section per unit time, N_{rt} , is equal to the measured maximum wave frequency, N_{rmax} .

In the following analysis Blasius' formula is used to calculate the value of λ_{iv} . Experimental values of λ_i being obtained, λ_{iD} can be determined by

$$\begin{aligned} \lambda_{iD} &= \lambda_i - 0.3164 Re_{go}^{-0.25} \\ &\approx \lambda_i - 0.3164 Re_{go}^{-0.25} \end{aligned} \quad (21)$$

On the other hand, λ_{iD} -value simply is proportional to a parameter $\bar{H} N_{rt} / (u_{go} Re_{go}^{0.5})$ in Eq.(20). This parameter can be calculated using experimental results. Hence, the λ_{iD} -value determined by Eq.(21) is plotted against the parameter $\bar{H} N_{rt} / (u_{go} Re_{go}^{0.5})$ in Fig.17. From this figure the constant C in Eq.(20) is obtained, and then Eq.(20) leads to

$$\lambda_{iD} = 5500 \frac{\bar{H} N_{rt}}{u_{go} Re_{go}^{0.5}} \quad (22)$$

Fig.19 Comparison between $(\lambda_i)_{cal}/\lambda_{iv}$ and $(\lambda_i)_{exp}/\lambda_{iv}$

Although the coefficients C' and C'' depend on tube diameter, their ratio ($C=8C''/C'$) is independent of diameter. Combining Eqs.(21) and (22) gives

$$\lambda_i = 0.3164 \frac{1}{Re_{go}^{0.25}} + 5500 \frac{\bar{H} N_{rt}}{u_{go} Re_{go}^{0.5}} \quad (23)$$

The interfacial friction factor calculated by Eq.(23), $(\lambda_i)_{cal}$, is compared with the experimental value, $(\lambda_i)_{exp}$, in Fig.18. Fairly good agreement between these two is considered to support the present analysis. Of course, Eq.(23) is too complex to apply in practice. However, the purpose of this analysis is achieved to establish the relation between interfacial friction factor and various parameters of interface. More detailed relationship will be presented in a later paper, including the effect of wave shape.

Figure 19 shows another comparison by the plots of $(\lambda_i)_{cal}/\lambda_{iv}$ against $(\lambda_i)_{exp}/\lambda_{iv}$. This figure indicates that interfacial friction factor can be over twice as large as the value obtained from Blasius' formula even in the ripple regime. In Figs.18 and 19 the largely deviated points in the region of large λ_i -value belong to the transition flow from ripple regime to disturbance wave regime.

6. Conclusions

The following conclusions can be drawn from this study, for interfacial friction factor and major parameters of interface under the conditions tested.

(1) Mean film thickness can be approximately determined as the distance from wall surface, where relative contact time η becomes 0.35.

(2) Mean film thickness is below 0.3 mm, while maximum wave height is three times the mean film thickness or more. Maximum wave frequency ranges from 100 l/s to 1000 l/s. Thus, it is concluded that gas-liquid interface even in ripple regime is quite rough.

(3) Propagation velocity of ripple is hardly affected by liquid flow rate and tube diameter, but it steeply increases with an increasing gas velocity.

(4) Interfacial shear force or stress must be evaluated phenomenologically by taking into consideration the additional drag force caused by various ripples in size and frequency. A new relation is introduced between interfacial friction factor and major parameters of interface.

References

- (1) Sekoguchi, K., et al., Bulletin of the JSME, Vol.20, No.145(1977-7), p.844.
- (2) Sekoguchi, K., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.39, No.317(1973-1), p.313.
- (3) Wallis, G. B., Papers presented at annual meeting of the AIChE, Tampa, Florida, (1968).
- (4) Robert, D. C. and Hanratty, D.E., Nuclear Research Memorandum, No.Q6(1961).
- (5) Wallis, G.B., ASME Paper 69-FE-46(1969).
- (6) Moeck, E. O., AECL-3656(1970).
- (7) Schlichting, H., Boundary Layer Theory, (1962), p.525, McGraw-Hill.
- (8) Nikuradse, J., Forschungsheft, 361(1933).