Int. J. Multiphase Flow Vol. 15, No. 6, pp. 893–900, 1989
Printed in Great Britain.
0301-9322/89 \$3.00 + 0.00

INTERPRETATION OF ATOMIZATION RATES OF THE LIQUID FILM IN GAS–LIQUID ANNULAR FLOW

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(*Received 7 September* 1988; *in revised form* 15 *April* 1989)

Abstract—For vertical gas–liquid annular flow the fraction of the liquid in the gas is controlled by the rate of atomization of the liquid film flowing along the wall and the rate of deposition of droplets entrained in the gas. Measurements of the rate of atomization are interpreted by a Kelvin–Helmholtz mechanism. Small wavelets on the liquid film are visualized to be entrained when wave-induced variations in the gas pressure cannot be counterbalanced by surface tension effects.

Key Words: annular flow, gas–liquid flow, atomization, entrainment

1. INTRODUCTION

In vertical annular gas–liquid flows liquid moves along the wall, with a mass flow rate W_{LF}, and as droplets entrained in the gas, with a mass flow rate W_{LE}. A knowledge of the fraction of the liquid entrained, $E = W_{LE}/W_L$, is of great importance in understanding this flow regime.

The magnitude of the entrainment, E, is controlled by two rate processes: the rate of atomization of the wall layer, R_A; and the rate of deposition of droplets, R_D. Recently, extensive measurements of R_D and R_A have been made in this laboratory (Schadel 1988; Leman 1985). The system studied was the upward flow of air and water in 2.54, 4.20 and 5.72 cm pipes.

The present paper explores the use of a Kelvin–Helmholtz instability mechanism to interpret the measurements of R_A. This theory suggests that wave growth is controlled by pressure variations associated with the inviscid flow of a fluid over a wavy surface. According to the Bernoulli equation, the compression of the streamlines at the crest causes a pressure decrease. If this suction cannot be balanced by the opposing force of surface tension, instability occurs. This instability is manifested by a rapid growth of the wave which could lead to its removal from the liquid surface.

At very low liquid flow rates the wall film is thin and covered by stable capillary ripples which seem to be associated with wave-induced variations of the shear stress at the surface (Hanratty 1983). Above a certain critical flow rate, W_{LFC} (Schadel 1988; Andreussi *et al.* 1985), large amplitude surges in the film flow rate, called roll waves or disturbance waves, are present.

The surface of these roll waves is highly disturbed. High-speed photographic studies by Woodmansee & Hanratty (1969) and by Whalley *et al.* (1979) have shown that atomization occurs by the removal of capillary ripples riding on top of the roll waves. The importance of roll waves in the atomization process is further emphasized by the observation that entrainment and atomization are negligible when roll waves are not present.

Woodmansee & Hanratty (1969) suggested that the ripples are removed from the surface of roll waves by a Kelvin–Helmholtz mechanism. This idea was supported by the experiments of Zanelli & Hanratty (1970) who measured the wavelengths of the ripples on top of the roll waves. Taylor (1940) developed a theory for R_A based on a Kelvin–Helmholtz mechanism. Tatterson (1975) applied this theory to annular flow. However, it has been very difficult to check his results because of a lack of information on the wave structure.

Therefore, a principal ingredient of this paper is the presentation of measurements of wave properties at the same conditions for which R_A was determined. Of particular importance to testing the theory is the determination of the intermittency (the fraction of the time roll waves are present, I) and the height of the roll waves, h_w.

2. KELVIN–HELMHOLTZ THEORY

Taylor (1940) considered a thick viscous liquid layer covered uniformly with capillary ripples of wavelength λ. He assumed the gas flow over the liquid surface could be considered inviscid and used Kelvin–Hemlholtz theory to calculate the rate of growth of unstable ripples. Taylor argued that the volume of liquid removed per unit area scaled as $\lambda^3/\lambda^2 = \lambda$ and that the rate of atomization per unit area scaled as

$$R_A \sim \frac{\lambda}{t_G}, \qquad [1]$$

where t_G is a time constant characterizing the growth of the unstable waves.

From these considerations it follows that

$$\tilde{R}_A = \frac{R_A}{U_G\sqrt{\rho_G \rho_L}} = f(\mathrm{We}_\lambda, \theta). \qquad [2]$$

Here U_G is the gas velocity, ρ_G is the gas density and ρ_L is the liquid density. Dimensionless group We_λ is a Weber number based on the wavelength,

$$\mathrm{We}_\lambda = \frac{\rho_G U_G^2 \lambda}{\sigma}, \qquad [3]$$

where σ is the surface tension. Dimensionless group θ is a measure of the effect of the liquid viscosity, μ_L, on wave growth,

$$\theta = \frac{\rho_L \sigma^2}{\rho_G \mu_L^2 U_G^2}. \qquad [4]$$

Tatterson (1975) has shown that θ is not important unless the liquid is very viscous so that for liquids with viscosities < 100 cP,

$$\tilde{R}_A = f(\mathrm{We}_\lambda). \qquad [5]$$

An additional relation can be obtained if one argues that atomizing waves are the fastest-growing waves. For a deep liquid this yields $\mathrm{We}_\lambda = \mathrm{const}$, so that

$$\tilde{R}_A = \mathrm{const}. \qquad [6]$$

Equation [6] does not describe measurements for annular flows for which $\tilde{R}_A$ is found to be a strong function of W_{LF}.

Tatterson (1975) therefore considered how Kelvin–Helmholtz theory is affected by the height of the liquid layer. He showed for very thin liquid layers that shear stresses exerted by the gas flow over the wave surface can be of equal (or greater) importance as the pressure. Tatterson argued that if this is the case waves will tumble and not atomize. This, then, could explain why ripples on the thin films between disturbance waves do not atomize. According to this interpretation, the role of the disturbance waves in the atomization process is that they intermittently present thick enough layers so that waves on their surface are dominated by pressure, rather than shear stress, variations.

Tatterson suggested that the wavelength of the atomizing waves would scale approximately with the height of the roll waves. For example, Zanelli & Hanratty (1970) found that λ/h_w varied from 3 to 8 for a 16.5 variation in h_w. (A value of $\lambda/h_w = 3$ to 4 seems to be more representative of the high velocity flows that will be considered in this paper.) The following modification of Taylor's analyses is, therefore, obtained for low viscosity liquids:

$$\tilde{R}_A = If(\mathrm{We}_{hw}). \qquad [7]$$

Here, I is the fraction of the time disturbance waves are present and the Weber number is defined with the height of the roll wave,

$$\mathrm{We}_{hw} = \frac{\rho_G U_G^2 h_w}{\sigma}. \qquad [8]$$

Tatterson also considered modifications of [7] that take into account the velocity profile in the gas and its influence on the pressure variations over wavy surfaces. The simplest way to do this is to use the friction velocity, u^*, in [7] rather than U_G:

$$\tilde{R}_A^* = If(\mathrm{We}_{hw}^*), \qquad [9]$$

$$\mathrm{We}_{hw}^* = \frac{\rho_G u^{*2} h_{Rw}}{\sigma}$$

and

$$\tilde{R}_A^* = \frac{R_A}{u^* \sqrt{\rho_G \rho_L}}. \qquad [10]$$

The following arguments for this substitution are given by Tatterson *et al.* (1977). Turbulent flow over a completely roughened surface is usually represented by

$$\frac{U}{u^*} = A + B \ln\left(\frac{y}{\varepsilon}\right). \qquad [11]$$

The velocity, U_λ, affecting the wave growth is at a distance from the surface which scales as the wavelength, $y = k_1 \lambda$. If the roughness scales as λ, then $\varepsilon = k_2 \lambda$ and

$$\frac{U_\lambda}{u^*} = A + B \ln\left(\frac{k_1 \lambda}{k_2 \lambda}\right). \qquad [12]$$

The r.h.s. of [12] is constant and U_λ is proportional to u^*.

Measurements of R_A by Schadel (1988) were obtained for upward flow of air and water in 2.54, 4.20 and 5.70 cm pipes. These are correlated quite well with the equation

$$\tilde{R}_A = \frac{k_A}{\pi D}(W_{LF} - W_{LFC}), \qquad [13]$$

where $k_A = 4.7$ ms/kg. This type result would suggest (Leman 1985) that Taylor's equation [6] is applicable in the form

$$\tilde{R}_A = I \text{ const.} \qquad [14]$$

One of the initial objectives of the present research was to determine if I is linearly dependent on $(W_{LF} - W_{LFC})$. This was found not to be the case. Therefore, $\tilde{R}_A$ must be related to wave properties through both I and h_w.

3. DESCRIPTION OF THE EXPERIMENTS

All the experiments were done with air and water flowing downward at 1 atm and 20°C.

The time-varying film height was determined in 2.54 and 4.20 cm pipes by measuring the conductance between two ring electrodes, mounted flush with the pipe wall. The 0.20 cm long electrodes were constructed of stainless steel and separated by a distance of 0.30 cm. The electrical circuits and the method of calibration are described elsewhere by Schadel (1988) and Asali *et al.* (1985b). These give a voltage (conductance) approximately proportional to liquid height and a zero signal for zero height.

Because roll waves are coherent around the circumference in 2.54 and 4.20 cm pipes, the ring electrodes provide a good measure of the average height of the roll wave. However, they do not give details about the small-scale variations at the crest of roll waves.

Measurements from the film height probes were sampled 500 time/s for 30 s to give 15,000 points. Depending on the wave frequency this procedure sampled 260–1140 waves for the 2.54 cm pipe and 180–690 waves for 4.20 cm pipe.

4. DETERMINATION OF WAVE PROPERTIES

The wave velocity, U_{RW}, is the best defined characteristic of the roll waves. This was measured by obtaining simultaneous height measurements with two probe pairs separated by a distance, Δz. The correlations between the signals at the two locations are measured for different time delays, Δt. A distinct peak at a time delay Δt_M is usually observed and the roll wave velocity is defined as $U_{RW} = \Delta z / \Delta t_M$.

The procedure suggested by Azzopardi (1979) and Azzopardi *et al.* (1979) was used to define roll wave frequency. The frequency power spectrum was determined and the peak is defined as the roll wave frequency, f_{RW}. This procedure was found to be in good agreement with a simple count of roll waves at flow conditions for which they can be identified from a film height tracing.

Roll wave intermittency is the most difficult quantity to determine. Both Chu & Dukler (1975) and Nencini & Andreussi (1983) have suggested that the wave amplitude probability distribution is bimodal and that this can be used to define a range of wave heights for roll waves.

Figure 1(a, b) gives an example of such a measurement. Here, the amplitude is defined as one-half the difference between a minimum in the film height trace and the subsequent maximum, as suggested by Nencini & Andreussi (1983). Two peaks are to be noted in figure 1b and the intermittency can be defined as the fraction of time waves with amplitudes >0.2 are present.

However, in many cases this bimodal distribution was not so evident, so a different procedure was followed. Individual waves and their amplitudes were determined according to the method suggested by Nencini & Andreussi (1983). A roll wave/ripple wave cutoff was arbitrarily chosen and the number of waves occurring above this point was counted. This number was compared with the frequency determined from the spectral analysis. The cutoff point was then adjusted and the process repeated until the "counted frequency" agreed with the spectral frequency. Once the roll waves were clearly defined, intermittency was calculated by summing the time lengths of all the roll waves and dividing this sum by the total sampling time.

Exact calibrations were not carried out for each run. Therefore the following procedure was used to calculate roll wave heights. The voltage signals corresponding to the heights of each roll wave that was identified were averaged and this value was divided by the time-averaged signal to get a ratio of roll wave height to film height. This was then multiplied by the measurements of film height made by Asali *et al.* (1985a) with the same equipment.

5. INFLUENCE OF WAVE PROPERTIES ON R_A

One of the main purposes of this paper was to obtain an understanding of how the empirically determined rate equation [13] is related to wave properties.

Schadel has made detailed comparisons of the measurements of wave frequency, wave velocity and wave spacing with the measurements of Azzopardi in a 3.20 cm tube. Good agreement was obtained. Some of these results are plotted in figures 2–7 vs the excess film flow rate, $\Gamma - \Gamma_0$, where $\Gamma = W_{LF}/\pi D$ and $\Gamma_0 = W_{LFC}/\pi D$, so that direct comparisons with [13] can be made. Values of W_{LFC} determined by Schadel (1988) were used. These corresponded to Re = 240 for the 2.54 cm tube and Re = 310 for the 4.20 cm tube, where Re = 4 $W_{LFC}/\pi D \mu_L$. Values of W_{LF} were calculated from the liquid throughput and values of E reported by Schadel (1988).

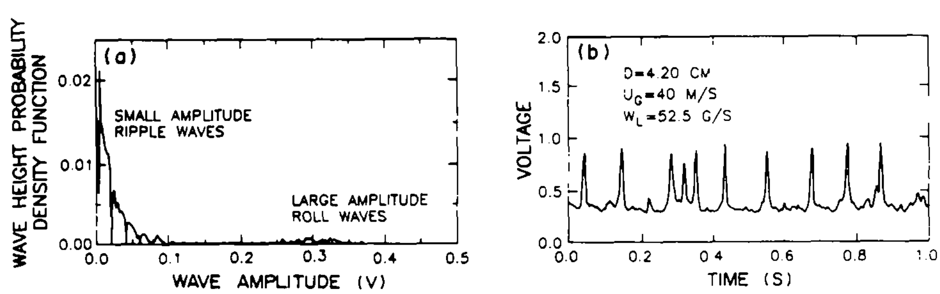

Figure 1. Measurements of the distribution of wave heights.

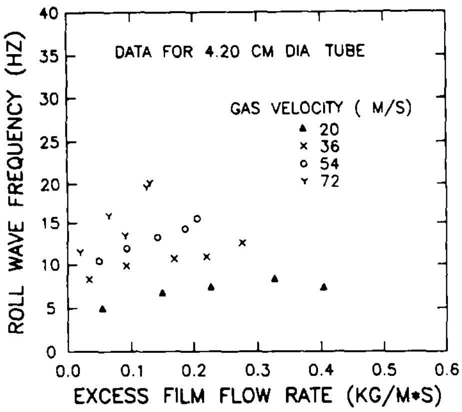

Figure 2. Roll wave frequency data for the 4.20 cm tube: effect of gas and liquid film flow rates.

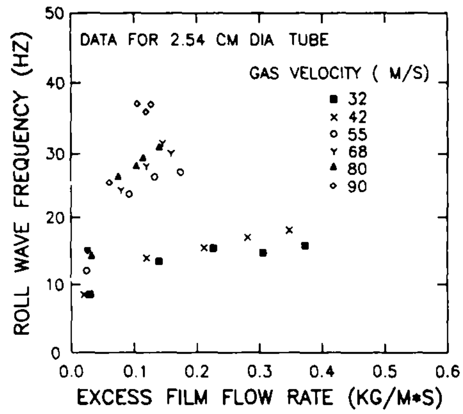

Figure 3. Roll wave frequency data for the 2.54 cm tube: effect of gas and liquid film flow rates.

Figures 2 and 3 indicate that roll wave frequencies increase only slightly with film flow rate at low gas velocities but become much more sensitive to $(\Gamma - \Gamma_0)$ at larger gas velocities. This is particularly evident in 2.54 cm tube, for which a large increase in roll wave frequency occurs at a gas velocity in excess of 42 m/s. The frequencies decrease with an increase in pipe diameter and with a decrease in gas velocity, so that they scale roughly with D/U_G.

Roll wave velocities show a weak dependence on liquid flow, increase with gas velocity and do not depend on pipe diameter. That is, they scale roughly with U_G and are of the order of 0.06 times the superficial gas velocity.

Roll wave spacings, defined as the quotient of wave velocity and frequency, decrease abruptly with increasing liquid flow at low liquid film flow rates and are roughly independent of gas velocity. At high flow rates they attain constant values which are proportional to the tube diameter, 1.5 m in the 2.54 cm tube and 2.5 m in the 4.20 cm tube.

As shown in figures 4 and 5, roll wave heights increase slightly with film flow rate at gas velocities < 50 m/s but become relatively insensitive to flow changes at gas velocities in excess of this value. Wave heights vary inversely with the square of the gas velocity and are not too sensitive to the change in pipe diameter.

Roll wave intermittencies, plotted in figures 6 and 7, are found to be independent of pipe diameter and gas velocity. They increase rapidly with increase in excess film flow rate at low values of this parameter but are approximately constant for large values [as suggested by Tatterson (1975)].

6. CORRELATION OF MEASUREMENTS OF R_A

Figure 8 explores a simplified application of [7] to correlate measurements of R_A. The intermittency is assumed constant and the height of the roll waves is assumed proportional to the

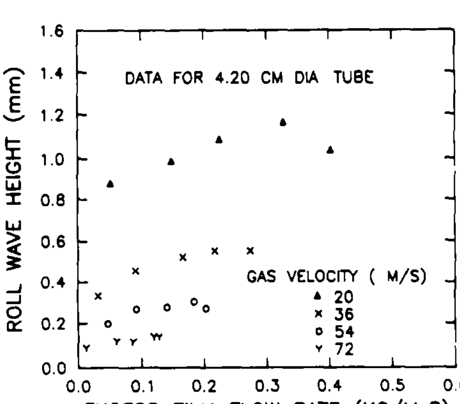

Figure 4. Roll wave height data for the 4.20 cm tube: effect of gas and liquid film flow rates.

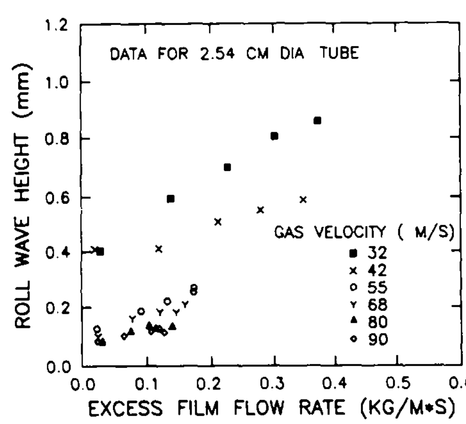

Figure 5. Roll wave height data for the 2.54 cm tube: effect of gas and liquid film flow rates.

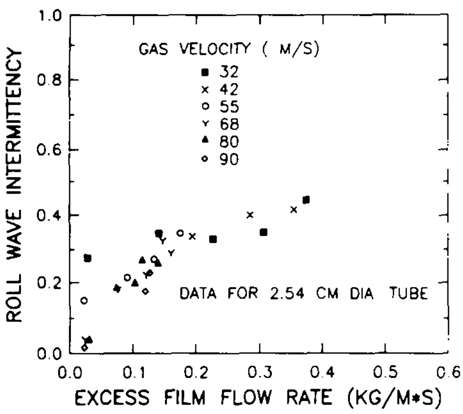

Figure 6. Roll wave intermittency data in the 2.54 cm tube: effect of gas and liquid film flow rates.

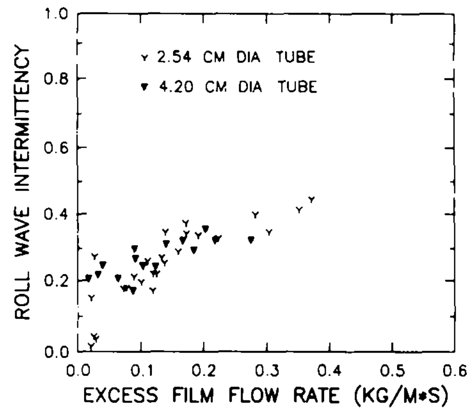

Figure 7. Roll wave intermittency: effect of pipe diameter.

average film height m. Therefore, $R_A/U_G(\rho_G\rho_L)^{1/2}$ is plotted against $\rho_G U_G^2 m/\sigma$. It is noted that this gives a poor correlation and, in particular, there is a strong effect of gas velocity which the correlation does not take into account. That is, there is a systematic decrease in $\tilde{R}_A$ at fixed Weber number with increasing gas velocity.

All of the measurements of R_A are correlated in accordance with [7] and [9] in figures 9 and 10. In figure 9 any systematic effects of pipe diameter or gas velocity are found to be within the error bounds of the measurements. Corrected friction velocities are determined from the pressure drop measurements of Asali *et al.* (1985b) and the measurements of R_D by Schadel (1988). From the pressure drop,

$$\tau_i = \frac{(D-2m)}{4}\left|\frac{\Delta P}{\Delta x}\right|. \qquad [15]$$

Now Moeck (1970) has pointed out that this measured stress is due both to surface drag and to momentum transfer associated with liquid interchange between the core and the film:

$$\tau_i = \tau_{is} + \tau_{iD}, \qquad [16]$$

where

$$\tau_{iD} = R_A(U_D - U_i). \qquad [17]$$

The droplet velocity is related to the gas velocity through the slip coefficient C_S,

$$U_D = C_S U_G. \qquad [18]$$

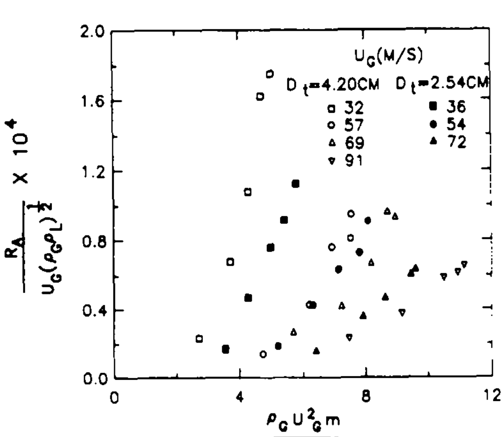

Figure 8. Correlation of measurements of R_A without the intermittency and the wave height.

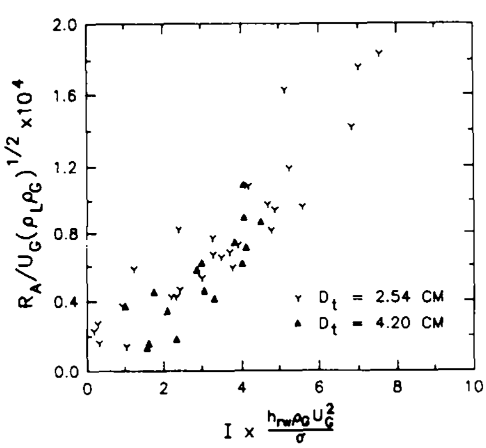

Figure 9. Correlation of measurements of R_A using the intermittency and a Weber number based on the roll wave height, h_{RW}, and the gas velocity, U_G.

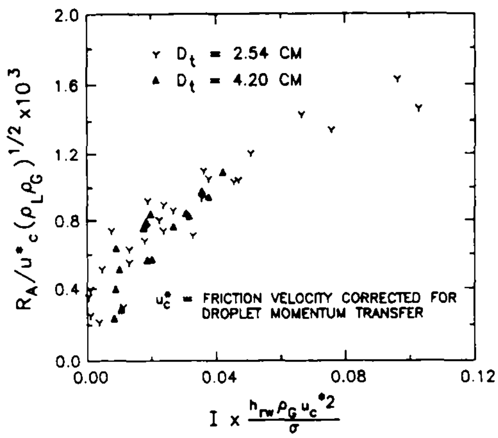

Figure 10. Correlation of measurements of R_A using the intermittency and a Weber number based on the roll wave height, h_{RW}, and the corrected friction velocity, u_c^*.

Moeck & Stachiewicz (1972) suggest that U_i be taken as the velocity of the interface and estimate

$$U_i \cong 1.66 U_{LF}, \qquad [19]$$

where U_{LF} is the average velocity of the liquid film.

Figure 10 uses a friction velocity defined with τ_{is},

$$u_C^* = \left(\frac{\tau_{is}}{\rho_G}\right)^{1/2}, \qquad [20]$$

rather than with $u^* = (\tau_i/\rho_G)^{1/2}$, since it was thought that this corrected friction velocity might be more closely related to the gas velocity close to the surface where wave-induced velocity variations are important. Since τ_{iD}/τ_i is typically about 0.2, this correction on the usually defined friction velocity does not have a strong effect on the correlation. It is noted from figures 9 and 10 that the use of [9] instead of [7] appears to do a slightly better job in correlating the measurements.

7. CONCLUDING REMARKS

Straightforward dimensional analysis, such as shown in figure 8, has not been successful in correlating measurements of R_A. Consequently, an empirical approach has been taken in this laboratory. Equation [13] represents a remarkably simple correlation for upward air and water over a wide range of gas and liquid velocities in 2.54, 4.20 and 5.70 cm pipes.

The major goal of this paper was to provide a physical understanding of [13] by studying the influence of liquid film flow rate on wave properties. The results in figures 4–7 show that both the roll wave height and the intermittency increase with increasing excess film flow rate.

This finding is consistent with equations developed by assuming atomization occurs through a Kelvin–Helmholtz instability. This idea is tested in figure 9. Since both I and $h_{rw} U_G^2$ increase with excess film flow rate, this plot is quite similar to the empirical correlation, [13]. The larger spread of the data using the abscissa in figure 9 rather than $(W_{LF} - W_{LFC})$ probably reflects the accuracy of the measurements of h_{RW} and I.

However, it is recognized that this paper does not prove that Kelvin–Helmholtz theory provides the correct interpretation. Further studies with liquids of different surface tension and viscosity are needed.

Acknowledgements—This work is being supported by the Department of Energy under Grant DOE FGO2-86E13556, the National Science Foundation under Grant NSF CBT 88-00980 and the Shell Companies Foundation.

REFERENCES

ANDREUSSI, P., ASALI, J. C. & HANRATTY, T. J. 1985 Initiation of roll waves in gas–liquid flows. *AIChE Jl* **31,** 119–126.

ASALI, J. C., HANRATTY, T. J. & ANDREUSSI, P. 1985a Interfacial drag and film height for vertical annular flow. *AIChE Jl* **31,** 895–902.

ASALI, J. C., LEMAN, G. W. & HANRATTY, T. J. 1985b Entrainment measurements and their use in design equations. *PhysicoChem. Hydrodynam.* **6,** 207–221.

AZZOPARDI, B. J. 1979 Disturbance wave velocity and spacing in annular two-phase flow. UKAEA Report AERE-R9347.

AZZOPARDI, B. J., FRYER, P. J. & FREEMAN, G. 1979 The frequency of disturbance waves in annular two-phase flow. UKAEA Report AERE-R9347.

CHU, K. J. & DUKLER, A. E. 1975 Statistical characteristics of thin wavy films: part 3, structures of large waves and their resistances to gas flow. *AIChE Jl* **21,** 583–593.

HANRATTY, T. J. 1983 Interfacial instabilities caused by air flow over a thin liquid layer. In *Waves on Fluid Interfaces*, pp. 221–259. Academic Press, New York.

LEMAN, G. W. 1985 Atomization and deposition in two-phase annular flow: measurement and modeling. Ph.D. Dissertation, Univ. of Illinois, Urbana.

MOECK, E. O. 1970 Annular–dispersed two-phase flow and critical heat flux. Ph.D. Thesis, Mechanical Engineering Dept, McGill Univ., Montreal, Quebec.

MOECK, E. O. & STACHIEWICZ, J. W. 1972 A droplet interchange for annular–dispersed, two-phase flow. *Int. J. Heat Mass Transfer* **15,** 673–653.

NENCINI, R. M. & ANDREUSSI, P. 1983 Studies of the behavior of disturbance waves in annular two-phase flow. *Can. J. chem. Engng* **40,** 459–466.

SCHADEL, S. A. 1988 Atomization and deposition rates in vertical annular two-phase flow. Ph.D. Dissertation, Univ. of Illinois, Urbana.

TATTERSON, D. F. 1975 Rate of atomization and drop size in annular two-phase flow. Ph.D. Thesis, Univ. of Illinois, Urbana.

TATTERSON, D. F., DALLMAN, J. C. & HANRATTY, T. J. 1977 Drop sizes in annular gas–liquid flows. *AIChE Jl* **23,** 68–76.

TAYLOR, G. I. 1940 Generation of ripples by wind blowing over a viscous fluid. In *The Scientific Papers of Sir Geoffrey Ingram Taylor*, Vol. 3 (Edited by BATCHELOR, G. K.), pp. 244–254. Cambridge Univ. Press, U.K.

WHALLEY, P. B., HEWITT, G. F. & TERRY, J. 1979 Photographic studies of two-phase flow using a parallel light technique. UKAEA Report AERE-R9389.

WOODMANSEE, D. E. & HANRATTY, T. J. 1969 Mechanism for the removal of droplets from a liquid surface by a parallel air flow. *Chem. Engng Sci.* **24,** 229–307.

ZANELLI, S. & HANRATTY, T. J. 1970 Relationship of entrainment to wave structure on a liquid film. Presented at the *Int. Symp. on Two-phase Flow*, Technion City, Haifa, Israel, Paper 2-1.