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USE OF MICROWAVES IN THE MEASUREMENTS OF FREQUENCIES AND AMPLITUDES IN LIQUID HOLD-UP FLUCTUATIONS

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Abstract—A technique based on absorption of microwave radiation by water molecules was developed for the measurement of liquid hold-up in gas–liquid systems, in particular in cocurrent flow of a gas and a water based liquid. The measuring set-up had to be empirically calibrated and the calibration line strongly depended on the mutual position of the radiation conducting waveguides and the tube containing the gas–liquid mixture: under certain circumstances a linear relationship between the amount of transmitted radiation and the value of liquid hold-up was obtained. The advantages of the technique are that a very flat beam of microwaves can be generated thus allowing to measure hold-up in a very narrow slice of the tube and that the device responds instantly to any change in hold-up.

The device was then used in connection with a spectrum analyzer to investigate the frequencies and amplitudes of hold-up fluctuations in upward cocurrent flow of air and water and air and corn sugar solution in a tube 12.9 mm i.d. It was found that the hold-up fluctuations were confined to low frequencies and that there was no particular regularity in their pattern. Only at higher gas and liquid flow rates the frequency–amplitude curves exhibited a peak value which may be associated with the occurrence of disturbance waves. The mean amplitudes of hold-up fluctuations were strongly dependent on the gas and liquid flow rates and for most liquid flow rates went through a maximum in the wavy-annular flow regime.

INTRODUCTION

The hold-up of gas and liquid, i.e. the fraction of the volume occupied by one or the other phase in a gas–liquid flow system, is an important parameter affecting, e.g. the pressure loss, the residence time etc. The techniques developed for measuring hold-up can be roughly divided into two groups: the lumped parameter techniques and the discrete parameter techniques.

The lumped parameter techniques provide the mean value of hold-up for the whole investigated volume. They rely on trapping the content by means of quick acting valves (Nichols 1965; Hughmark & Pressburg 1961; Hewitt 1963; Govier & Short 1958, and others), on weighing the section with gas–liquid flow (Hewitt 1957; Kamei & Oishi 1956; Colquhoun-Lee & Stepanek1978, and others), or on the measurement of the electrical conductance of the gas–liquid mixture (Casagrande *et al.* 1962; Silvestri 1963; Achwal & Stepanek 1976; Dhanuka & Stepanek 1978; Begovich & Watson 1978, among others).

In the discrete (or local) parameter technique the value of hold-up is measured in a small part of the volume of the investigated equipment. Measurements of radioactivity or attenuation of γ and X-rays have been used, e.g. by Casagrande *et al.* (1962), Perkins *et al.* (1961), Bogart & Spight (1964), Kennett *et al.* (1976), Schrock & Selph (1963) and Pike *et al.* (1965). The main disadvantage of these techniques is the inevitable health hazard.

The electrical conductance technique has been used for hold-up measurements in a small volume by various investigators, such as Collier & Hewitt (1961), Gill *et al.* (1965), Hewitt & Longrove (1963), Tomida & Okazaki (1974), Achwal & Stepanek (1976) and Begovich & Watson (1978) among others. Electrical capacitance was employed in hold-up measurements by Collier (1962), Rosehart *et al.* (1975) and Yasuda & Yasukawa (1974) among others.

Microwave absorption has been used in measurements of the water content in amorphous mixtures such as margarine (Kraszewski 1971). Other applications involved measurements of the hold-up of organic coolants (Stuchly *et al.* 1973) and of the density of hydrogen (Wegner & Smetana 1972). An excellent book reviewing techniques used for measuring hold-up and other two-phase flow parameters has been published by Hewitt (1978).

Numerous papers have been published on measurement of gas and/or liquid hold-up in cocurrent flow in pipes and various attempts have been made to develop models for the prediction of phase hold-ups. Many excellent reviews of these and other aspects of two-phase flow have been published by Wallis (1969), Govier & Aziz (1972) and Hewitt & Hall-Taylor (1970) among others.

The oscillatory nature of two-phase flows is clearly noticeable in the case of plug, slug and wavy-stratified flows. However, substantial fluctuation of parameters such as pressure or pressure drop can be observed even in relatively smooth flow patterns. Slug velocities were measured by numerous investigators, such as Griffith & Wallis (1961), Street & Tek (1965), Nicolitsas & Murgatroyd (1968), Dukler & Hubbard (1975) and Rosehart *et al.* (1975); the latter measured also slug frequencies. Velocities as well as separation times and distances of large disturbance waves in annular flow were measured by Hall-Taylor *et al.* (1963) and Nedderman & Shearer (1963). Tomida & Okazaki (1974) measured the fluctuations in film thickness and analyzed the results for periodicity. The amplitude of the fluctuations was about 40% of the mean film thickness in annular flow and some 70–90% of the fluctuations were due to random components.

EXPERIMENTAL

Measurements of liquid hold-up were undertaken in vertical perspex tubes 12.9 and 25.4 mm i.d. and 185 cm long; the wall thickness in both cases was approx. 1 mm. Air was used as the gas phase and the liquid phase was water and a solution of corn sugar with a viscosity 9.13×10^{-3} kg/ms at 20°C. The flow rates of the liquid ranged from 8.34×10^{-6} to 1.38×10^{-4} m^3/s, and those of the gas from 4.72×10^{-4} to 5.66×10^{-3} m^3/s at prevailing temperature and pressure. The temperature of the fluids was maintained in the range 21–24°C and the pressure at the exit of the experimental tube was virtually atmospheric. The flow regimes encountered in the study were slug, froth, wavy annular and mist flow. Pressure drop measurements were also taken and are reported elsewhere (El-Ayouty 1979).

A technique using a microwave signal was developed for measuring the hold-up of liquids, particularly water based. The method takes advantage of the fact that transmission of microwaves is strongly affected by water molecules as compared with air and some solid materials (e.g. perspex); the latter two had a negligible effect on the experiments reported here.

The measuring circuit consisted of a power supply and modulator unit connected to a narrow range (8.2–10.5 GHz) oscillator. The oscillator was operated at a frequency of 9.5 GHz which was found to give the largest transmission loss, although the latter was only little affected by frequency within the operating range of the oscillator. The microwave signal was modulated with a 1 kHz square wave and transmitted along a rectangular waveguide through an isolator, power level attenuator, calibrated attenuator and wavemeter to a transducer which was penetrated by the tube containing the gas–liquid mixture. The isolator prevented reflected waves from re-entering the oscillator. The power level attenuator was used to set the level of the signal and the calibrated attenuator served to compensate for the reduction in the intensity of microwaves in the "constant output signal" technique described below. The signal transmitted through the tube was detected by a square-law detector. The output from the detector was 1 kHz signal whose amplitude varied in response to the fluctuations in the two-phase flow system. The signal from the detector was amplified by a narrow band 1 kHz amplifier and, in the case of measurement of average hold-up, the signal was further passed through an integrating unit and recorded on a chart recorder.

The assembly for hold-up measurements using microwaves was first tested using the "constant output signal" technique. For the purpose of calibration, the liquid hold-up was measured directly by the trapping technique using two pneumatic valves mounted immediately at the entry and at the exit from the test tube. Moving the transducer along the test tube revealed no difference in the output signal as long as the flow rates of gas and liquid remained unchanged, thus suggesting that the variation in hold-up along the tube was negligible: under these circumstances it was possible to equate the local hold-up to its mean value in the whole tube. In

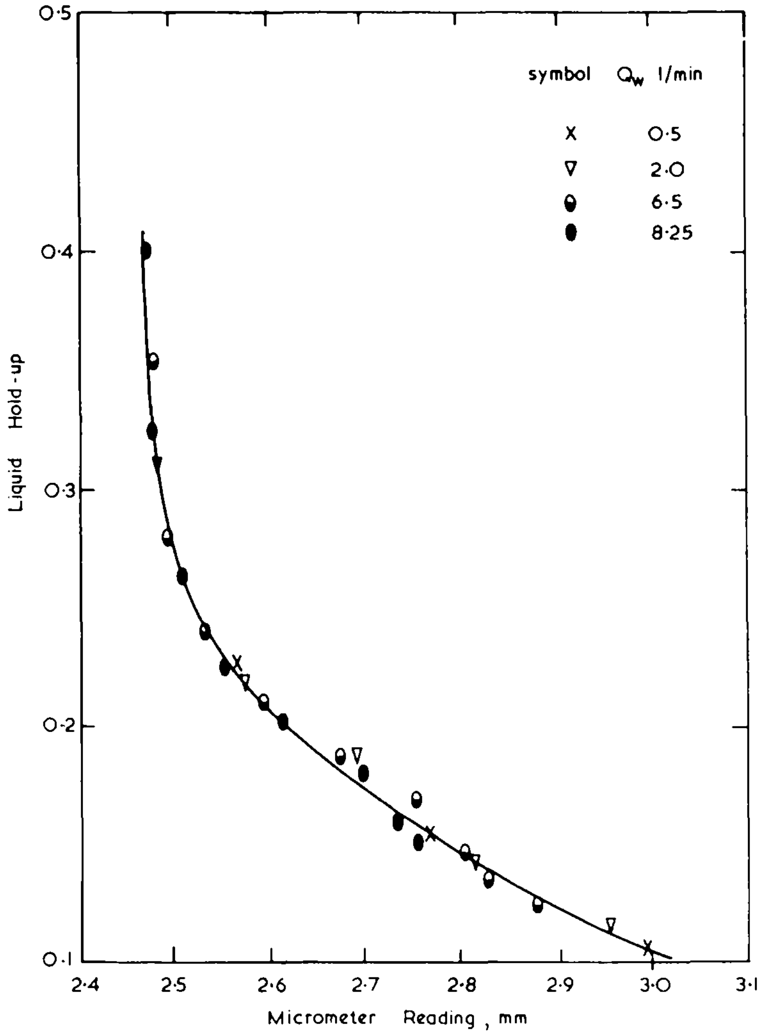

Figure 1. Calibration of the measuring circuit for the 10.16 × 22.63 mm waveguide.

order to improve the accuracy of the trapping technique, each measurement was repeated five times and the mean value was calculated; this reduced the standard error to about 2.5%.

The early results presented in figure 1 indicated that the relationship between the hold-up and the setting of the micrometric screw of the calibrated attenuator could be represented by a single line for the 12.9 mm tube and a wave guide 10.2 × 12.7 mm within a wide range of gas and liquid flow rates for flow patterns ranging from slug to annular-mist flow.

It was further established that the shape and the position of the calibration curve was strongly affected by the geometry of the system consisting of the two wave guides, the transducer and the tube. The effect of the change from a central to an off-centre position of the tube with respect to the waveguides is demonstrated in figure 2, while that of the thickness of the transducer is shown in figure 3. The reason for the strong effect of the system geometry on the calibration curve lies in the fact that the signal collected by the outlet waveguide and registered by the detector results from a complex combination of absorption, reflection and refraction of the original microwave input with quite a substantial proportion of the signal escaping detection on the sides of the waveguide. Some light has recently been thrown on this complex process by the work of Shariatmadar (1981) who analyzed the spatial distribution of microwaves after passage through a smooth water annulus. This study revealed that the distribution was a rather complex function of the film thickness and the angle from the vertical

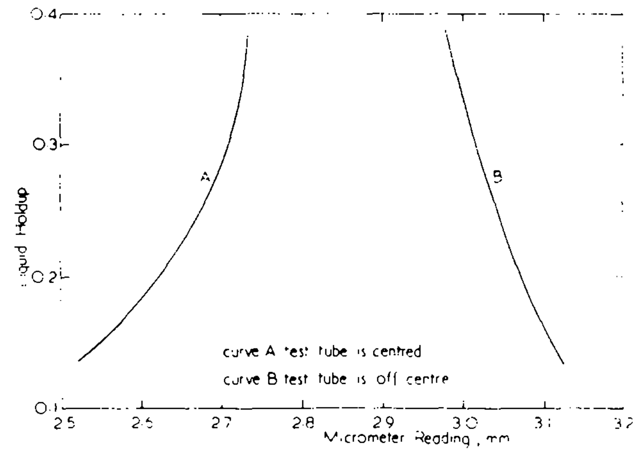

Figure 2. Effect of the mutual position of the tube and waveguide on calibration.

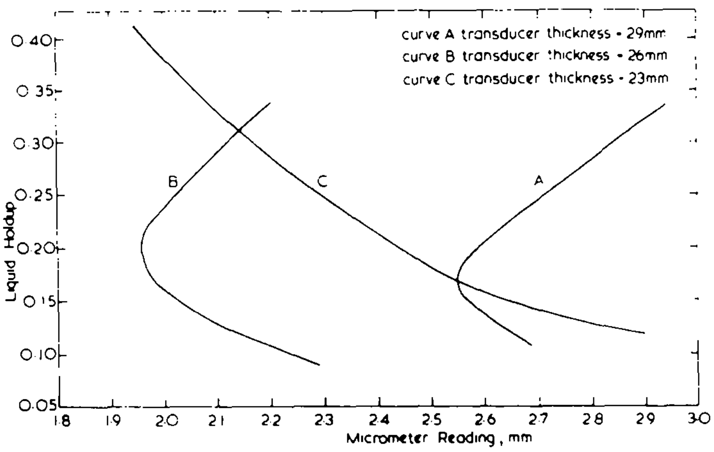

Figure 3. Effect of the transducer thickness on the calibration.

plane of symmetry, the shape of the derived distribution has been qualitatively confirmed by experiments.

Although the work of Shariatmadar supplied an explanation for the peculiar effect of the geometry of the set-up on the dependence of the output signal on hold-up, it did not provide any basis for a quantitative prediction of such effect. Consequently, the best geometrical arrangement has to be found empirically, however, once this has been done, a virtually straight line calibration can be obtained as is seen from figure 4 for the 12.9 mm tube and a 2 × 37 mm waveguide: the narrow waveguide was chosen to reduce the height of the investigated section. An empirical calibration also took account of the absorption, albeit very low, in the perspex wall of the tube and in air.

Microwaves absorption is not influenced by temperature as it is effected by bonds within water molecules.

THEORY OF MICROWAVE DETECTION OF HOLDUP OSCILLATIONS

The transducer and detector theory (figure 7) can be applied to any pattern of gas–liquid flow, however, for illustration, annular flow will be considered. There are two simple cases: (i) the wave pattern keeps the same shape and moves with a velocity U, and (ii) the pattern oscillates but it does not move through the transducer. In the first case the output voltage V_t

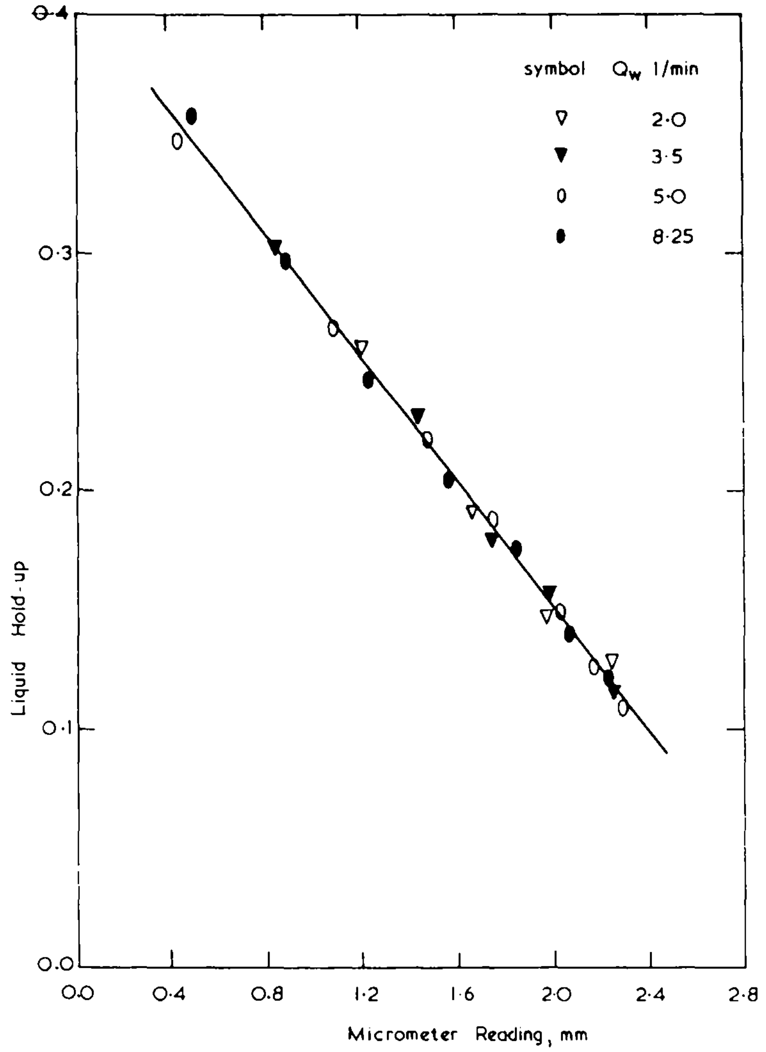

Figure 4. Constant output calibration for the 2 × 37 mm waveguide.

rises and falls as the peaks and troughs of the ripples pass through the transducer. The frequency of the voltage fluctuations is

$$f_u = \frac{U}{\lambda_0} \qquad [1]$$

where λ_0 is the wavelength of the moving pattern.

In the second case, as the pattern oscillates with frequency f_s, then V_t oscillates at the same rate. The final output frequency is a combination of f_u and f_s, together with the amplitudes of the oscillations.

The low frequency of the ripple pattern modulates the high frequency microwave input signal of angular frequency ω to give the following output

$$V_t = A(1 + m(t)) \cos(\omega t + \phi(t)). \qquad [2]$$

The time variations of the amplitude is $(1 + m(t))$ and the phase shift $\phi(t)$. The current i through the diode in the detector circuit can be described according to Betts (1970) by the

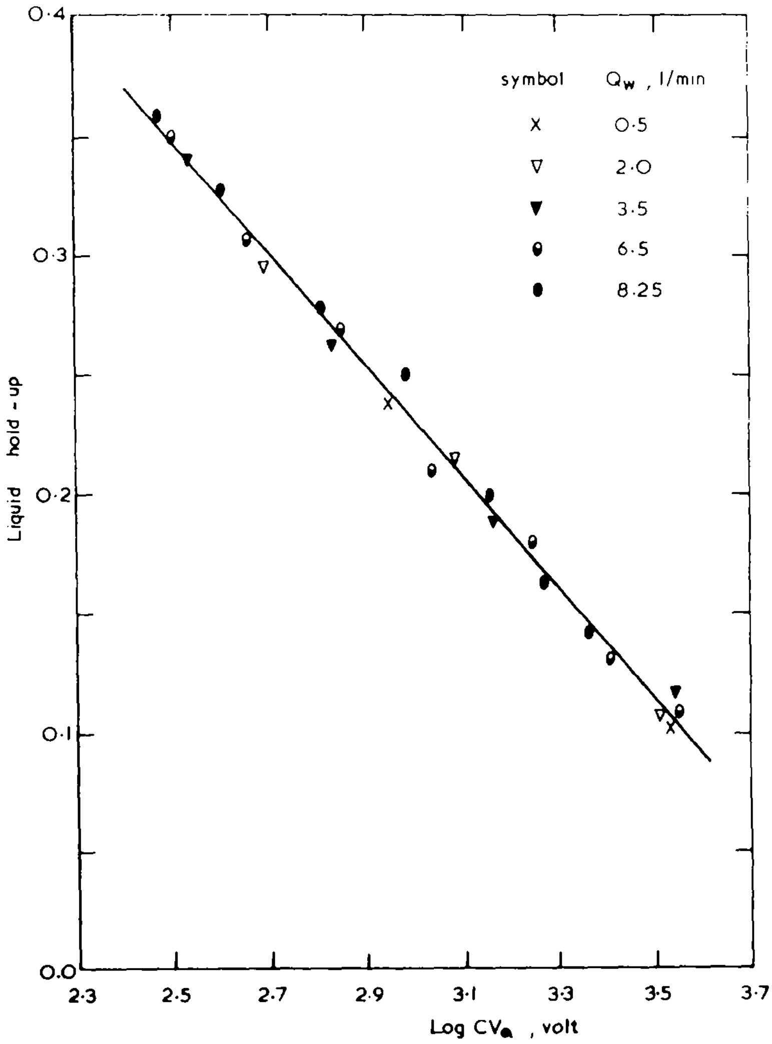

Figure 5. Constant input calibration for the 2 × 37 mm waveguide—air/water system.

following equation

$$i = K_1 V_t + K_2 V_t^2 + \ldots \text{terms of no importance} \qquad [3]$$

where K_1 and K_2 are constants. The capacitor in the detector circuit filters out the microwave frequency leaving only the low frequency component, thus the first term in V_t is eliminated as it oscillates at angular frequency ω. The contribution of the second term is

$$\begin{aligned} K_2 V_t^2 &= K_2 A^2 (1 + m(t))^2 \cos^2(\omega t + \phi(t)) \\ &= \frac{K_2 A^2 (1 + 2m(t)) + m^2(t)}{2} [1 + \cos 2(\omega t + \phi(t))] \end{aligned} \qquad [4]$$

where A is a constant.

The high frequency term $2(\omega t + \phi(t))$ is also eliminated by the capacitor leaving a low frequency current passing through the resistor as

$$i_1 = \frac{K_2 A^2}{2} (1 + 2m(t) + m^2(t)) \qquad [5]$$

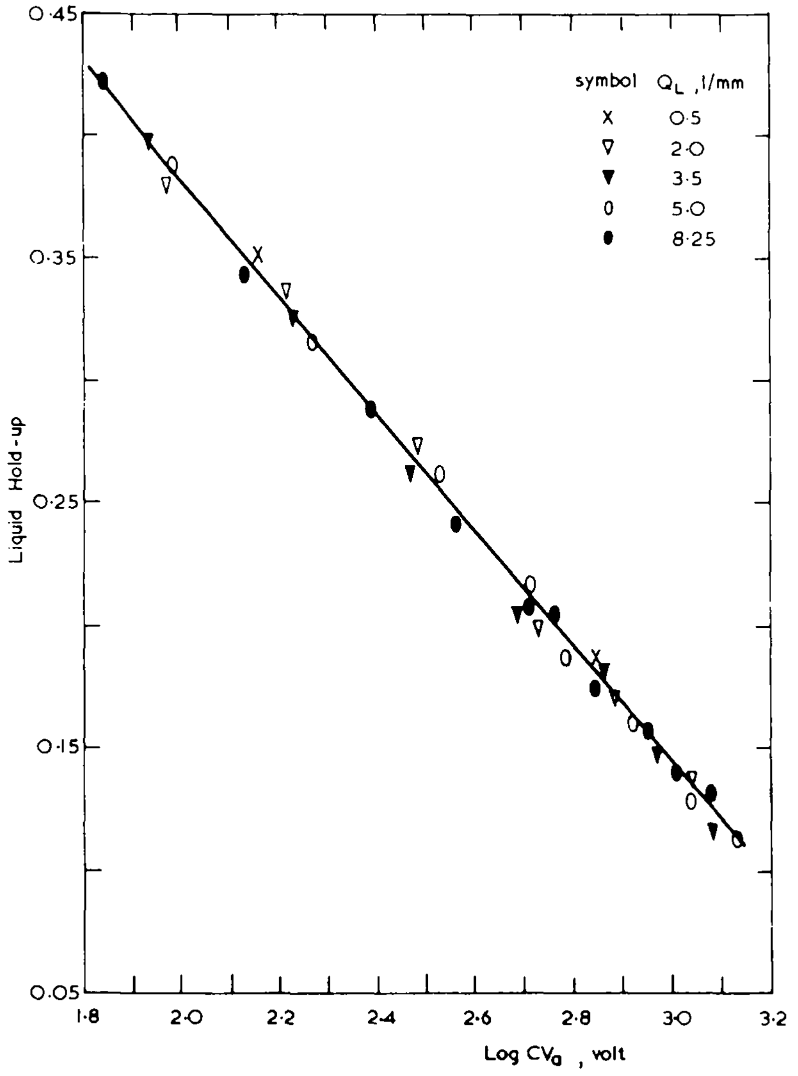

Figure 6. Constant input calibration for the 2 × 37 mm waveguide—air/viscous liquid system.

and the voltage V_a across this resistor R is

$$V_a = i_1 R \qquad [6]$$

If $|m(t)|$ is small so that $m^2(t) \ll |m(t)|$, then the last term on the r.h.s. of [5] can be neglected. Thus,

$$i_1 = \frac{K_2 A^2}{2}(1 + 2m(t)) \qquad [7]$$

and the frequency of the pattern $m(t)$ can be readily detected as the output of the circuit varies in proportion to $m(t)$. But if $m^2(t) \not\ll |m(t)|$, then some distortion results.

In order to obtain an estimate of the error, assume that $m(t) = m \cos \omega_m t$ where $\omega_m = 2\pi f_m$ and f_m is a combination of f_s and f_u. The maximum currents is from [5]

$$i_2 = \frac{K_2 A^2}{2}(1 + 2m + m^2) \qquad [8]$$

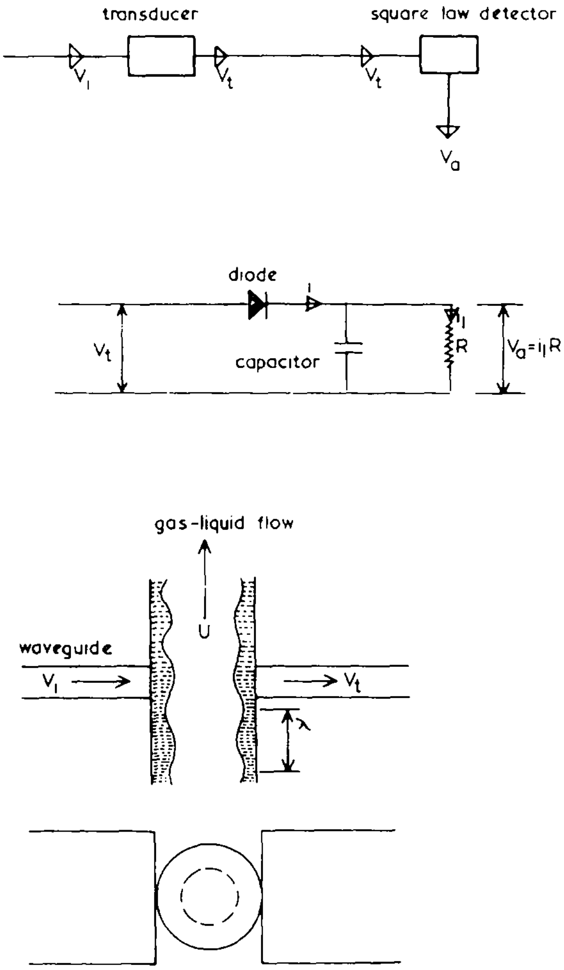

Figure 7. Application of transducer and detector theory to gas-liquid flow.

and the minimum current i_3 is

$$i_3 = \frac{K_2 A^2}{2}(1 - 2m + m^2). \qquad [9]$$

Dividing [9] into [8] to eliminate the diode constant K_2 and solving for m that satisfies the condition that $m = 0$ when $i_2 = i_3$ gives

$$m = \frac{i_2^{1/2} - i_3^{1/2}}{i_2^{1/2} + i_3^{1/2}}. \qquad [10]$$

If the quadratic term in [5] is neglected, then m is obtained as

$$m = \frac{1}{2}\frac{i_2 - i_3}{i_2 + i_3}. \qquad [11]$$

In an example it is assumed that $i_3 = \frac{1}{2} i_2$. Then from [10] it is calculated that $m = 0.172$ whereas the simple [11] gives $m = 0.167$, which introduces an error of 2.9%.

The purpose of this analysis was to provide a practical estimate for the detection system acting as a square law detector, i.e. the output (i_1 or V_t) is proportional to A^2. Thus i_2 and i_3 are measured by observing the maximum and minimum excursion of the needle of the meter of the detecting amplifier. Then m can be estimated using [10] or, if the ratio i_2/i_3 is not very large, the simpler [11]. The ratio of m^2 to $2m$ is a measure of the deviation from the square law detection and thus indicates the ability of the detector to follow accurately the variation of the amplitude of the received microwave signal.

INSTRUMENTATION FOR MEASUREMENTS OF HOLD-UP OSCILLATIONS

In the investigation into the character of the fluctuations in hold-up, the output from the amplifier in figure 1, apart from being smoothened by the integrator and recorded on the chart recorder in order to evaluate the mean value was also subjected to frequency analysis. A spectrum analyser model 1510 from Solartron Electronic Group Ltd was connected to the exit from the amplifier and employed at its lowest range of frequencies, thus measuring amplitudes for frequencies ranging from 0.1 to 25.6 Hz at 0.1 Hz intervals. The amplitude resolution was 0.1 dB, the noise level was accepted as −60 dB. The averaging interval for the development of the frequency-amplitude curve was set at 128 cycles which took 21.3 min to accomplish. The input signal was selected by means of the input attenuator control at 10 V_{rms}. Then the output voltage from the analyser is obtained as

$$V_{2\mathrm{rms}} = \frac{10}{10^{-(\mathrm{dB}/20)}}. \qquad [12]$$

Assuming a sine wave, the variation ΔV_0 of the output voltage from the amplifier is

$$\Delta V_0 = \sqrt{(2)}\, V_{2\mathrm{rms}}. \qquad [13]$$

From figures 6 and 7 it can be seen that the liquid hold-up R_L is related to the voltage output from the detector V_a as

$$R_L = A_1 + A_2 \log CV_a. \qquad (14)$$

After differentiation on introduction of differences it is obtained that the difference in liquid hold-up ΔR_L is related to the difference in the voltage output from the detector ΔV_a as

$$|\Delta R_L| = \frac{A_2}{2.3}\frac{\Delta V_a}{\bar{V}_a}. \qquad [15]$$

Taking into account that the amplification factor of the amplifier relating V_0 to V_a was constant, it follows that

$$|\Delta R_L| = \frac{A_2}{2.3}\frac{\Delta V_0}{\bar{V}_0} \qquad [16]$$

where the average output from the amplifier $\bar{V}_0$ was obtained from the chart recorder as described earlier.

RESULTS AND DISCUSSION

Data of mean hold-up acquired during the investigation into hold-up fluctuations were compared with the Lockhart–Martinelli correlation in figures 8 and 9. Agreement is rather modest in view of the fact that logarithmic scales are used in the graphs.

Examples of frequency-amplitude curves are shown in figures 10 and 11. The curves were obtained at different settings on the voltage divider, a change of the setting produced an upward

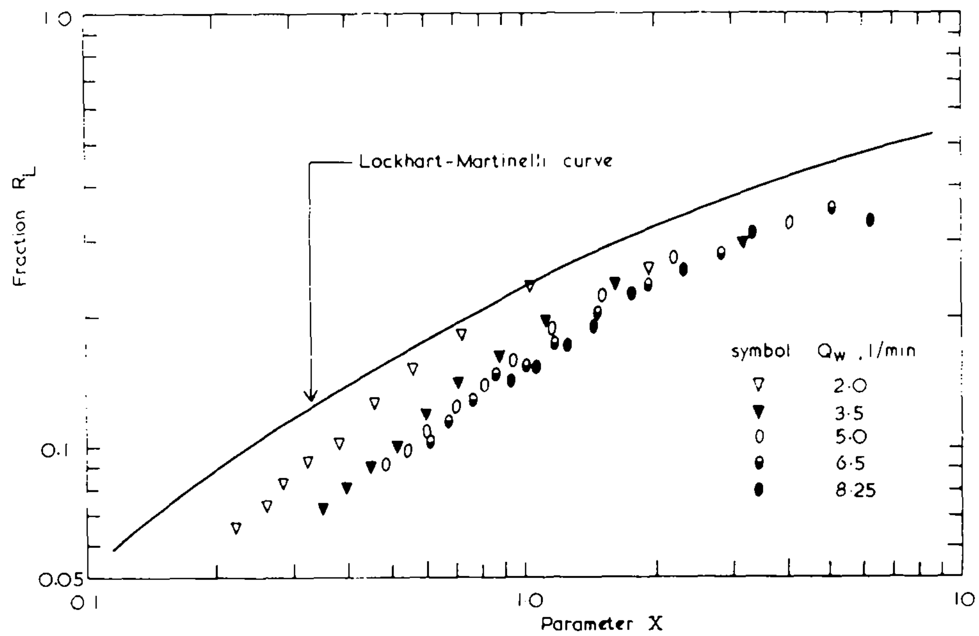

Figure 8. Comparison of the hold-up measurements in the 12.9 mm tube with the Lockhart-Martinelli correlation (air/water).

or downward shift of the curves. In figure 12, four curves from figures 10 and 11 were reduced to the same divider setting of output to input ratio of 1:600. Frequency analyses were performed for six water flow rates between 8.34×10^{-6} m^3/s and 1.38×10^{-4} m/s and for twelve gas flow rates ranging from 4.72×10^{-4} m^3/s to 5.66×10^{-3} m^3/s for both water and corn sugar solution in the 12.9 mm tube. The frequency curves remained fairly horizontal at low frequencies up to 1-2.5 Hz depending on the flow rate of liquid, after which they fell rather rapidly down to noise level at about 10 Hz. At higher frequencies distinct peaks appeared at the transition between the horizontal and declining part of the curves. In some instances, especially at high gas and liquid flow rates, the peaks were preceded by shallow troughs.

The flatness of the frequency-amplitude curves in the low frequency range indicates the absence of any regular oscillatory pattern. Even most of the peaks were rather broad indicating a rather low preference for the corresponding wave length. Only in some cases the occurrence of sharp peaks suggested some regularity in the pattern which was attributed to the existence of large disturbance waves. The frequency-amplitude curves for the viscous solution were generally similar to those obtained for water.

Mean amplitudes were evaluated from the frequency-amplitude graphs as integral means between the lowest frequency of 0.1 Hz and the so-called "cut-off" frequency. The latter was fixed at such position on the curve where the amplitude fell 3 dB below the calculated mean. The results were then interpreted as absolute and relative mean holdup fluctuations. The former were calculated from [16] and the latter were obtained by dividing the absolute fluctuations by the mean value of hold-up for the given combination of flow rates. The absolute mean hold-up fluctuations as a percentage of the tube volume are presented in figures 13 and 14 as functions of the gas and liquid flow rates for water and corn sugar solution, respectively. The curves for water show a maximum with respect to the gas flow rate. The effect of an increase in the liquid flow rate is to reduce the maximum and shift it towards higher gas flow rates. Also, with increasing liquid flow rate, the fluctuations at low gas flow rates are reduced while the opposite happens at high gas flow rates. Observed boundaries between flow patterns are included in figure 13, the maximum seems to appear in the wavy-annular flow. An inspection of figures 13 and 14 indicates that the result of a comparison between absolute mean fluctuations of hold-up

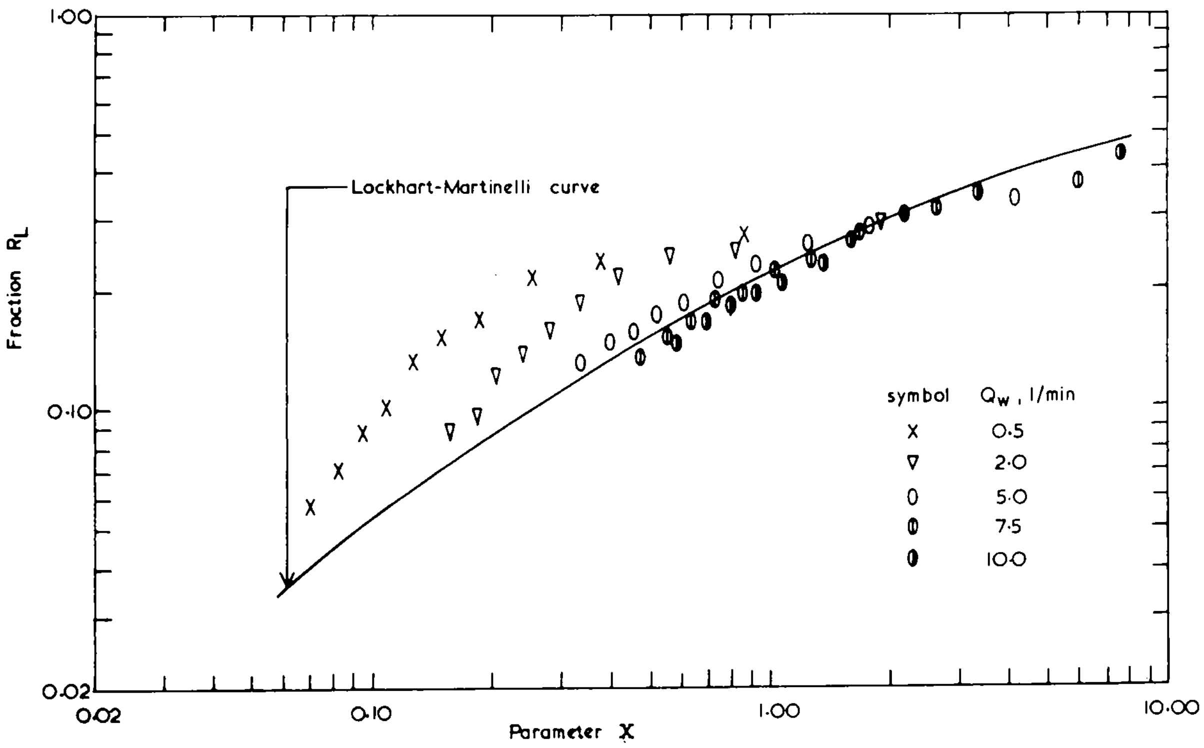

Figure 9. Comparison of the hold-measurements in the 25.4 mm tube with the Lockhart–Martinelli correlation (air/water).

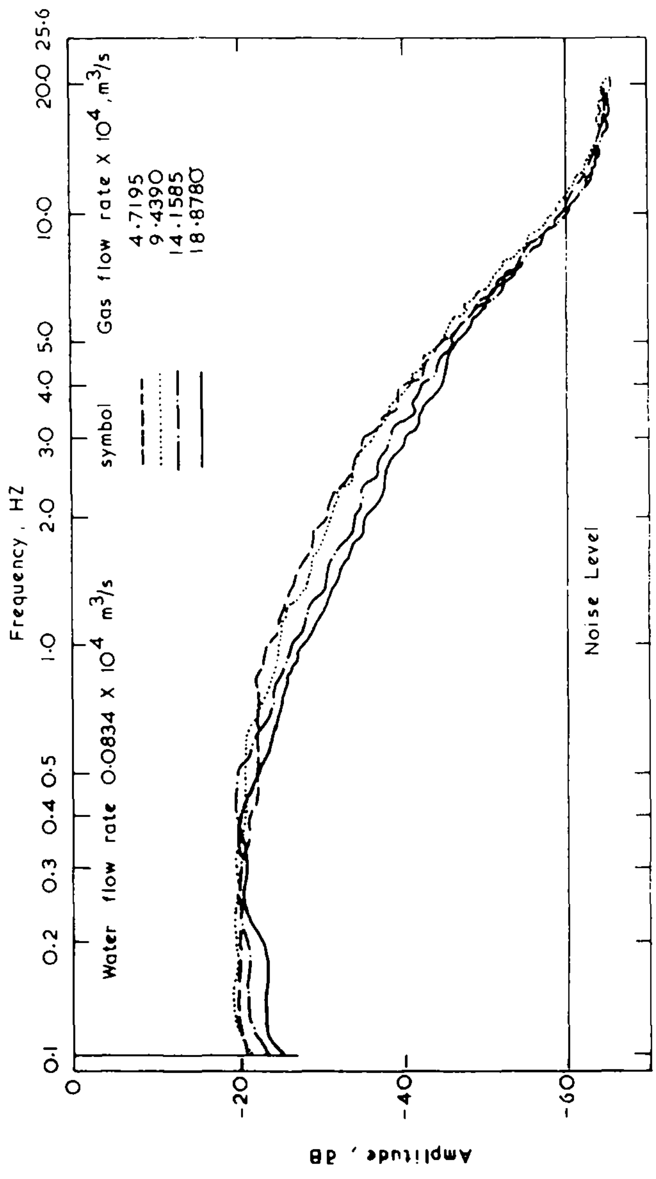

Figure 10. Frequency–amplitude curves for low water flow rate.

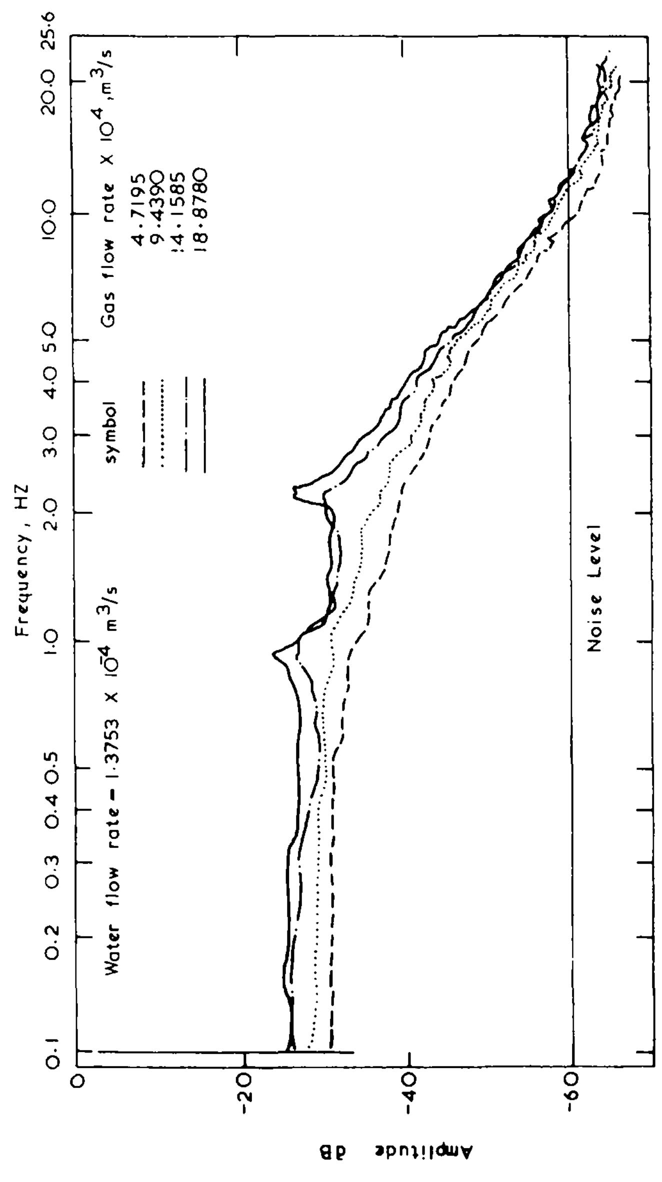

Figure 11. Frequency-amplitude curves for high water flow rate.

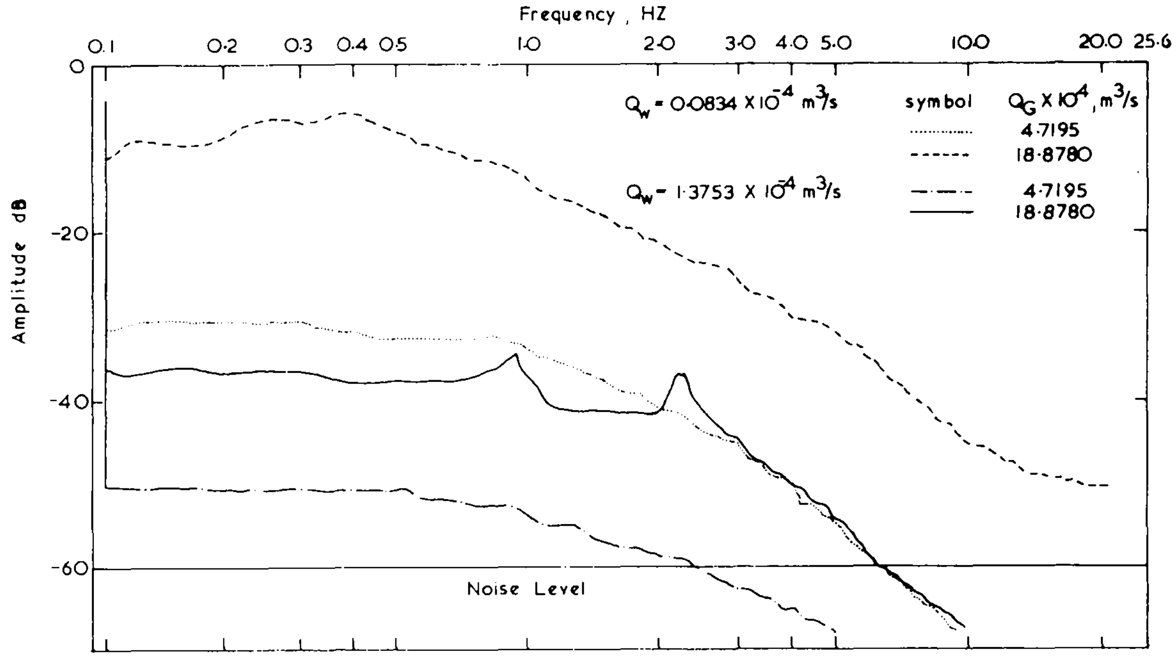

Figure 12. Comparison of frequency-amplitude curves at different water flow rates.

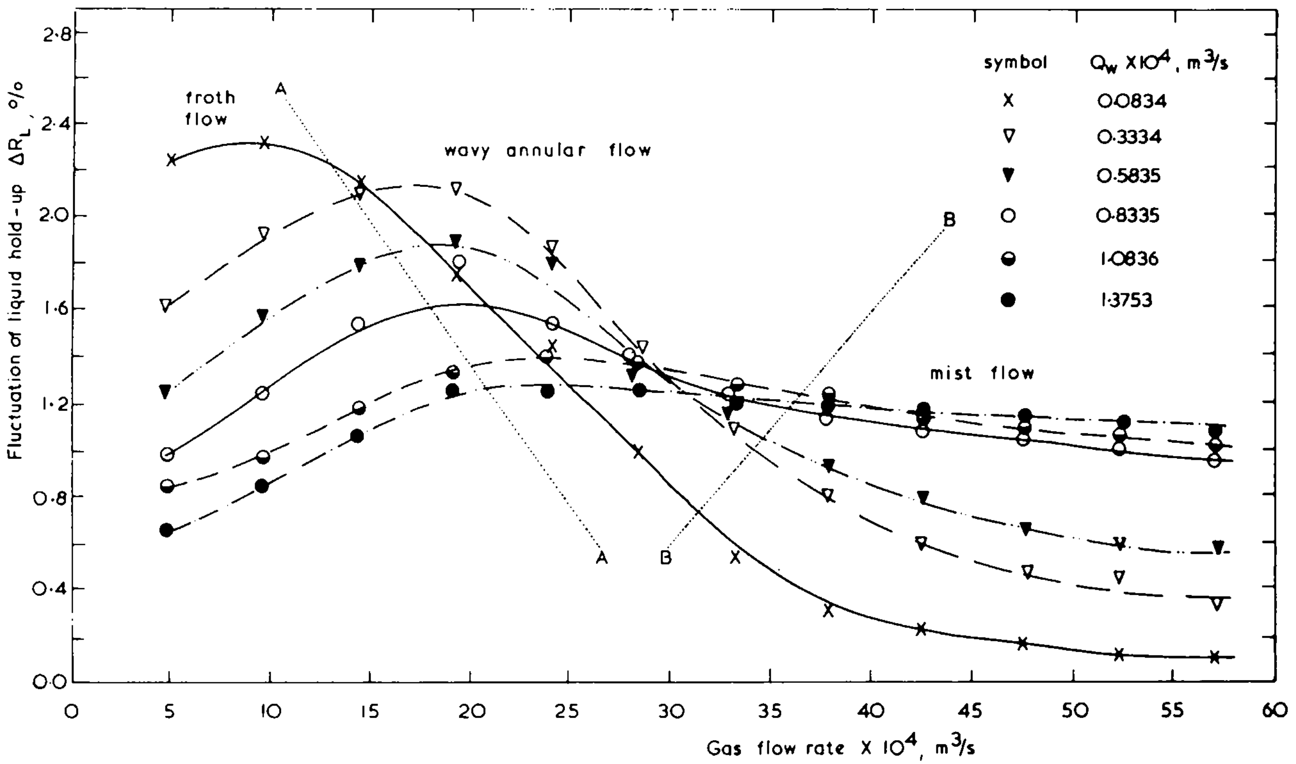

Figure 13. Absolute hold-up fluctuations in air-water flow.

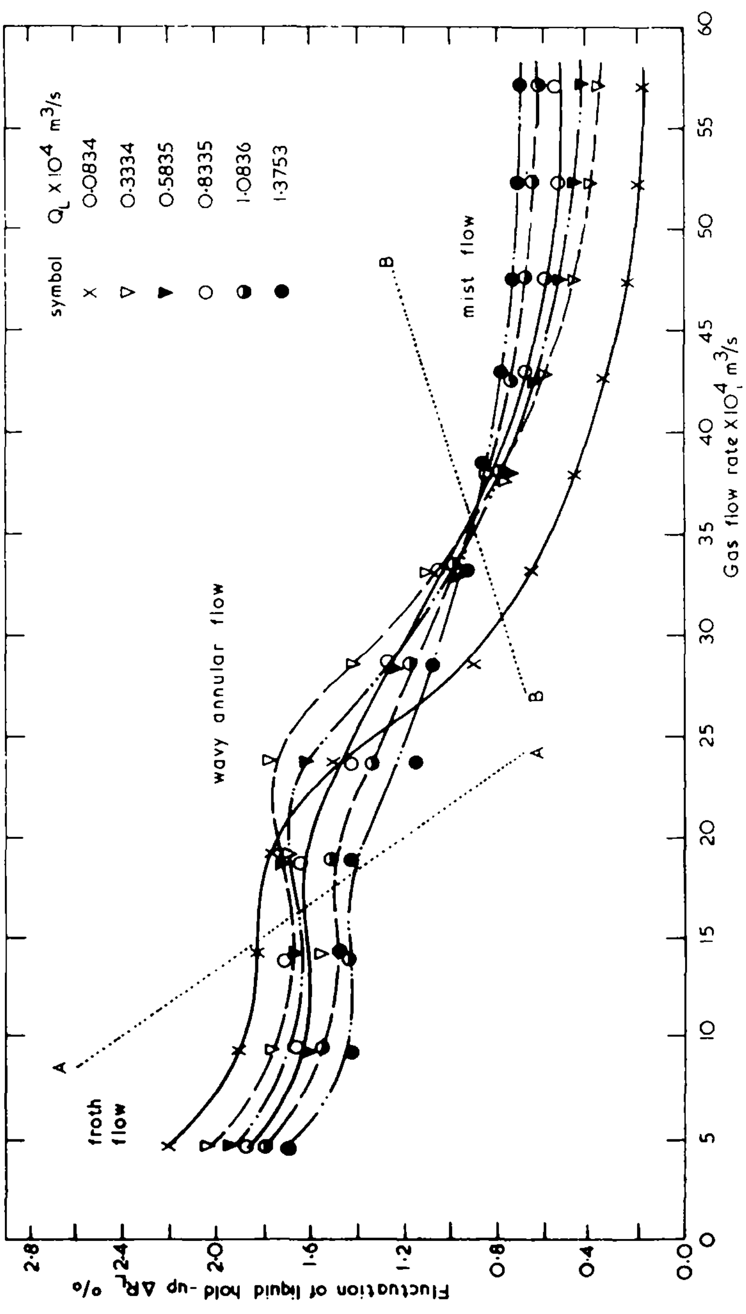

Figure 14. Absolute hold-up fluctuations in air–corn sugar solution flow.

in the corn sugar solution and in water depends on the liquid and gas flow rates. The fluctuations in the viscous liquid were higher at low gas flow rate, probably due to an increased tendency towards slugging. At high gas flow rates the fluctuations were about the same in both liquids at the lowest liquid flow rate, but they were significantly lower in the corn sugar solution at high liquid rates of flow. Also, there appears to be a change in the shape of the curves and the maxima virtually disappeared in figure 14. Moderate variations in temperature resulting in variations in viscosity in the range 7.35–8.33 cP were probably responsible for the increased scatter of the data in figure 14. Relative mean fluctuations of hold-up are presented in figure 15 for water and in figure 16 for the corn–sugar solution.

The cut-off frequencies represent the limit beyond which the contribution of the fluctuations becomes insignificant. The variations of the cut-off frequencies with gas and liquid flow rates for the two investigated liquids are shown in figures 17 and 18.

The peaks appearing in some frequency-amplitude curves are indicative of a certain periodicity in the fluctuations of hold-up. From figures 19 and 20 it appears that the peak frequencies increase with both the liquid and gas flow rates and that they are always higher in the air–water than in the air–corn sugar system. The dependence of the absolute amplitudes of the peaks on the gas and liquid flow rates is quite complicated as can be seen from figures 21 and 22.

The obvious candidate for the periodic phenomenon revealed by the occurrence of peaks in the frequency–amplitude curves are the disturbance waves investigated by Hall-Taylor *et al.* (1963). There were substantial differences between this study and the work of Hall-Taylor, who used a tube 3.18 cm i.d. and 6.71 m long and also much lower liquid superficial velocities. A comparison between the frequencies of the disturbance waves measured by Hall-Taylor and the amplitude peaks obtained in this study is shown in figure 23. In spite of the mentioned disparity in the conditions of the two studies, the differences in the frequencies are not very large.

No frequency–amplitude data were collected for the 25.4 mm tube because of the difficulties experienced with adjusting the level of the signal without causing an overload of the spectrum analyser.

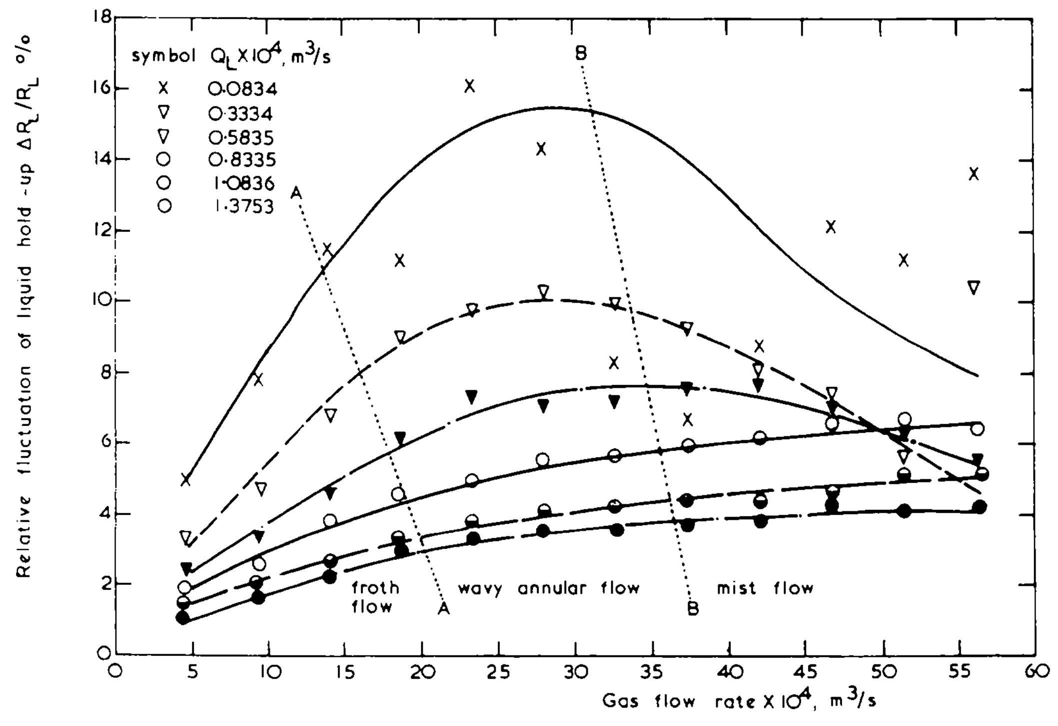

Figure 15. Relative hold-up fluctuations in air–water flow.

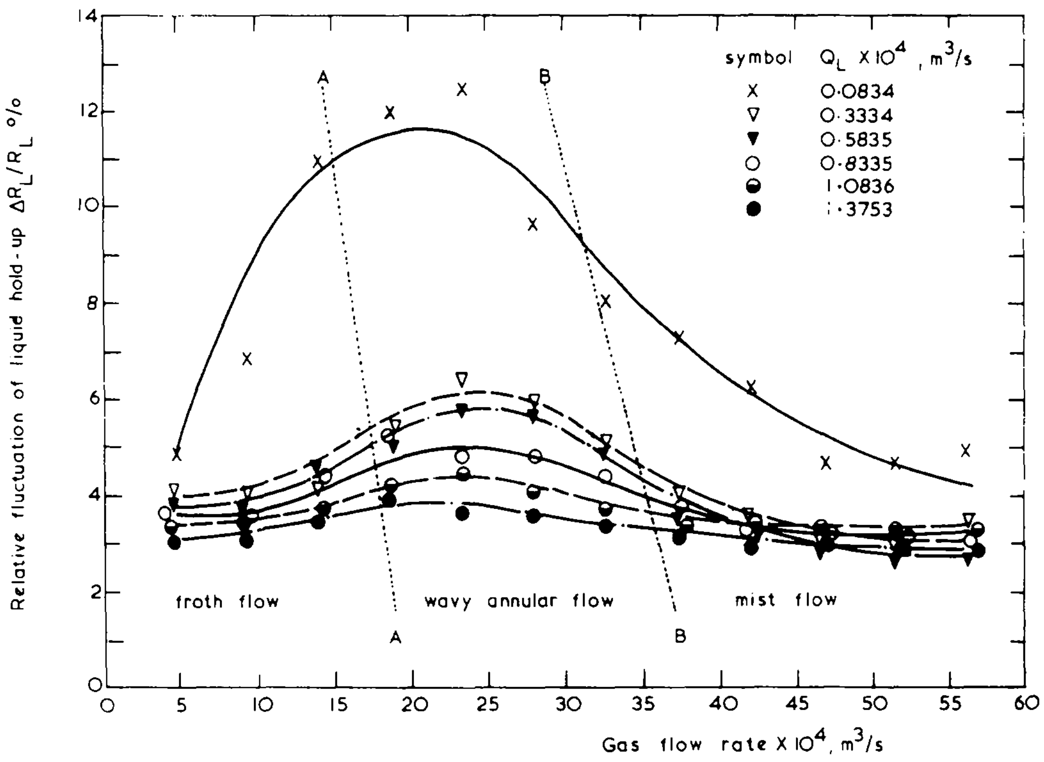

Figure 16. Relative hold-up fluctuations in air–corn sugar solution flow.

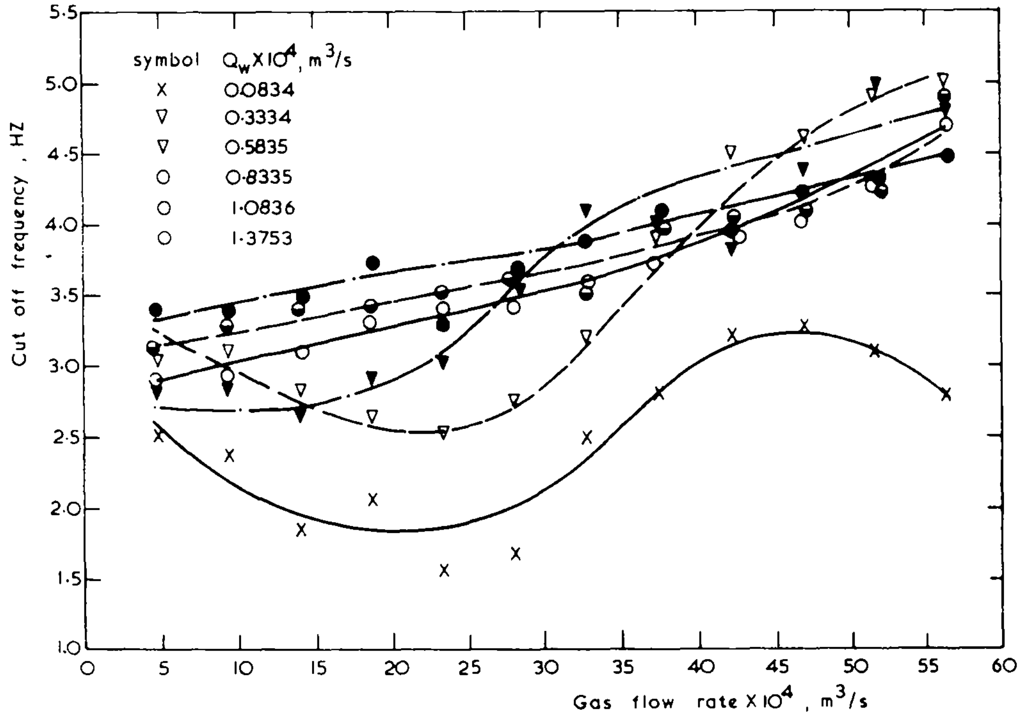

Figure 17. Variation of cut-off frequency with air and water flow rate.

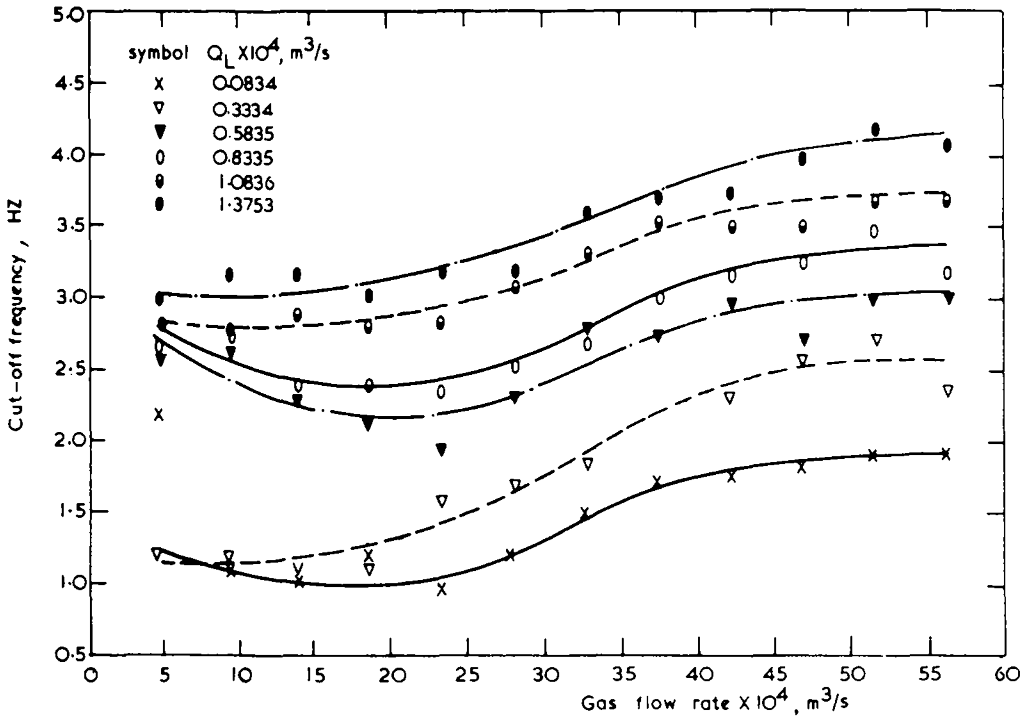

Figure 18. Variation of cut-off frequency with air and corn sugar solution flow rate.

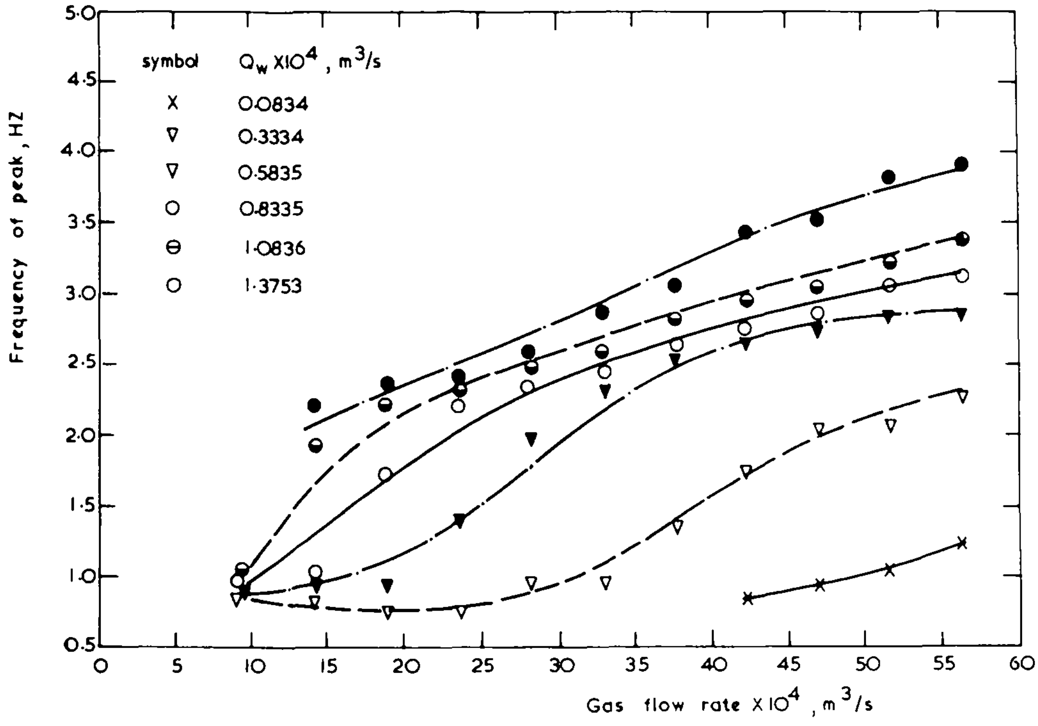

Figure 19. Variation of peak frequency with air and water flow rates.

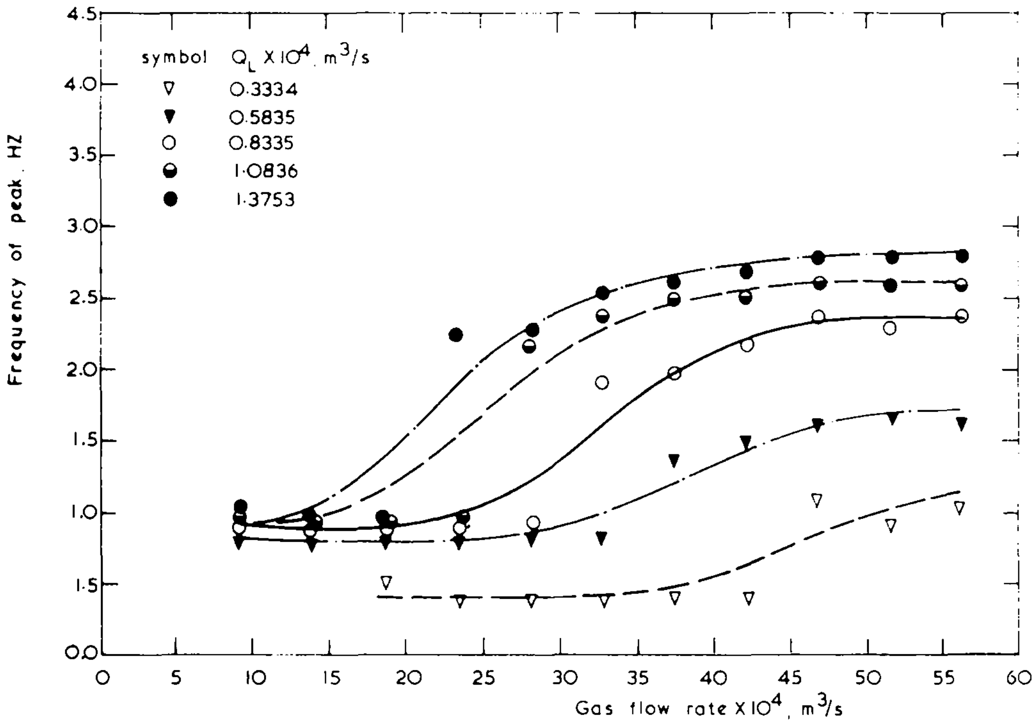

Fig. 20. Variation of peak frequency with air and corn sugar solution flow rates.

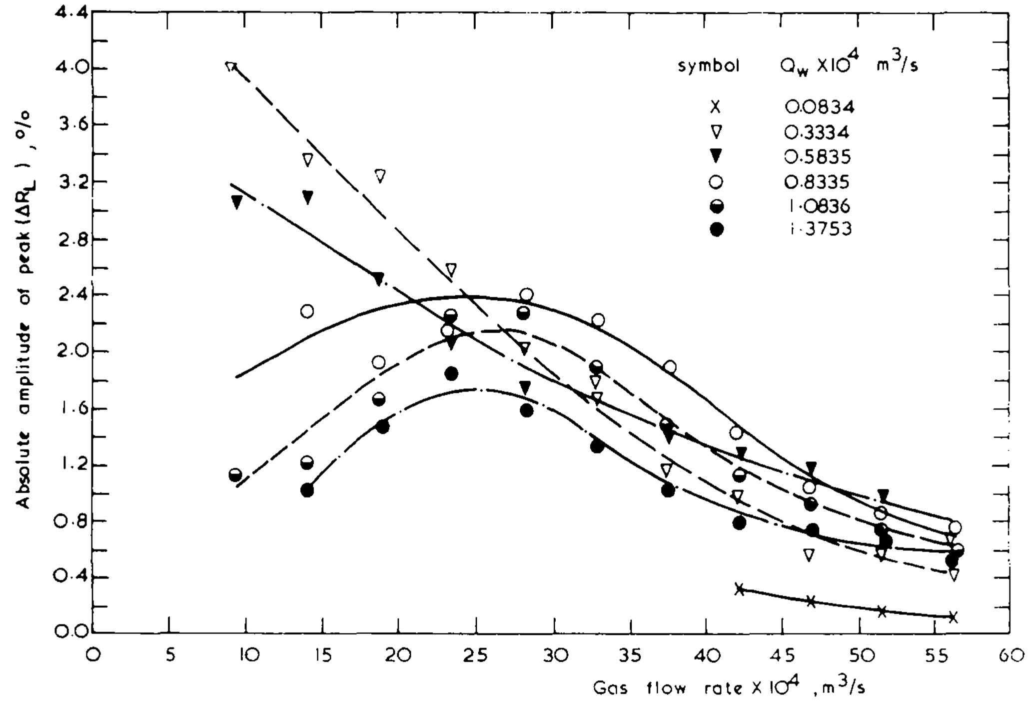

Figure 21. Dependence of absolute peak amplitudes on air and water flow rates.

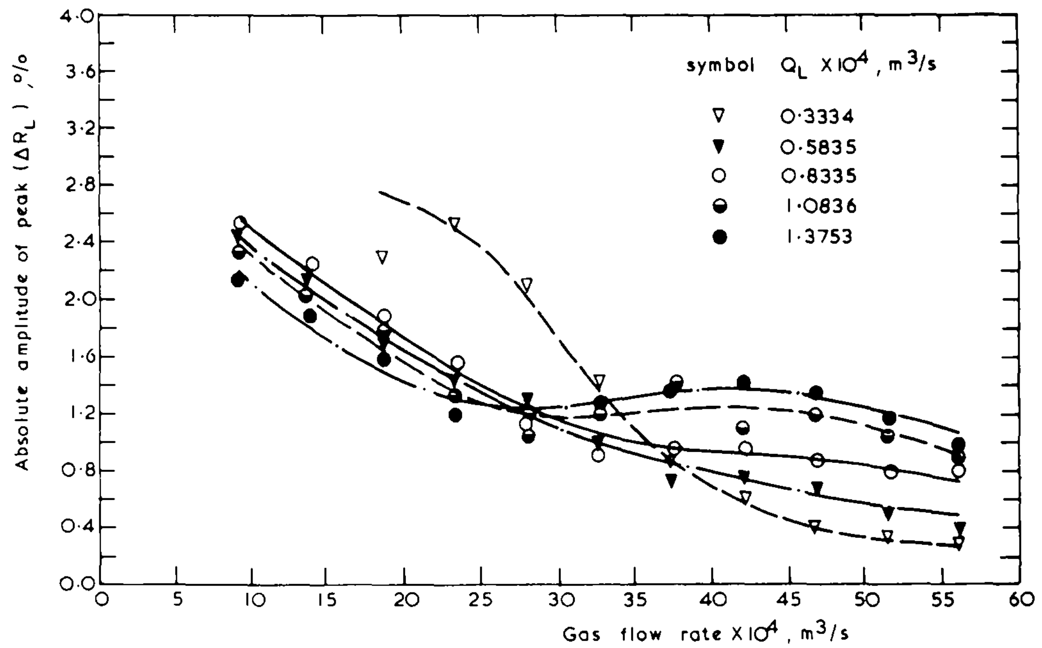

Figure 22. Dependence of absolute peak amplitudes on air and viscous solution flow rates.

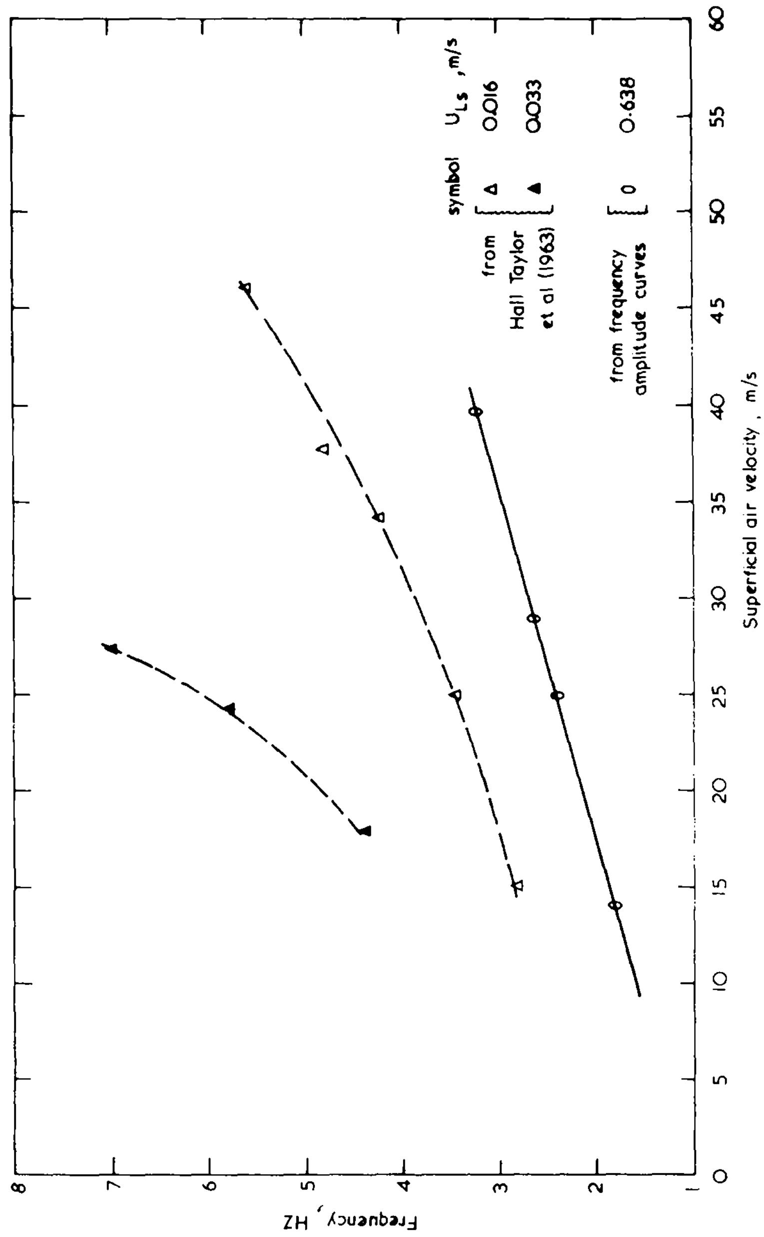

Figure 23. Comparison of the effect of velocities on the frequency of disturbance waves.

CONCLUSIONS

A technique for measuring liquid hold-up in gas–liquid flow based on absorption of microwaves in the range of 9–10 GHz was developed. The set-up for the measurement of hold-up required empirical calibration, but once this was done, it could be used for continuous measurements in a narrow section of a tube with an inside diameter 12.9 mm.

The developed technique was employed to measure fluctuations of liquid hold-up in a narrow 2 mm wide window through the tube using a spectrum analyzer and an X–Y plotter.

Two liquids were used in the study, viz. water and corn sugar solution. It was found that the frequency–amplitude curves were fairly flat at low frequencies and fell off rather quickly around 2–3 Hz. At higher liquid and gas flow rates peaks appeared at the frequency amplitude curves which were probably related to the disturbance waves investigated by Hall-Taylor *et al.* (1963). It was discovered that the mean amplitudes of the absolute as well as the relative fluctuations of hold-up depended on the gas and liquid flow rates and, in the majority of cases, they exhibited a maximum in the annular flow region. The mean fluctuations in the viscous solution were less than in water except at very low gas flow rate where the viscous liquid showed an increased tendency towards slugging.

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