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TWO-PHASE ANNULAR AND DISPERSED FLOWS

GUEST EDITORS
P. ANDREUSSI, B. J. AZZOPARDI AND T. J. HANRATTY

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TWO-PHASE ANNULAR AND DISPERSED FLOWS

Selected Papers Presented at the International Symposium on Two-Phase Annular and Dispersed Flows
University of Pisa, Italy, 24–29 June 1984

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P. ANDREUSSI, B. J. AZZOPARDI and T. J. HANRATTY

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FOREWORD

When a gas and a liquid flow through a pipe at a large velocity, an annular configuration is reached for which part of the liquid is transported along the wall as a wavy liquid film and part as droplets entrained in the gas phase. This is the most poorly understood pattern observed for gas–liquid flows. An excellent review of the state of the art up to 1970 is given in the book *Annular Two-Phase Flow*, by G. F. Hewitt and N. S. Hall-Taylor. The papers published in this volume of *PhysicoChemical Hydrodynamics* were selected from presentations at an International Symposium on Two-Phase Annular and Dispersed Flows held in Pisa, Italy, 24–29 June 1984, to assess progress since 1970 and to focus on basic physical phenomena that control phase distribution and friction losses. This Symposium was organized by P. Andreussi (Università di Pisa), B. J. Azzopardi (AERE Harwell), M. Cumo (Università di Roma), J. M. Delhaye (CEN Grenoble), A. E. Dukler (University of Houston), T. J. Hanratty (University of Illinois), G. F. Hewitt (AERE Harwell), F. Mayinger (Technische Universität München) and S. Zanelli (Università di Pisa). It was sponsored by the Dipartimento di Ingegneria Chimica, Pisa, and was supported by Ente Nazionale Energie Alternative, Consiglio Nazionale delle Ricerche, Università di Pisa.

The principal theoretical problem, in describing annular flows, is the prediction of the fraction of the liquid entrained in the gas. This, in turn, requires an understanding of two rate processes controlling entrainment, the rate of entrainment of liquid from the wall film and the rate of deposition of droplets from the gas to the liquid surface.

The liquid film that flows along the wall is dominated by long wavelength two-dimensional frothy flow surges, called disturbance waves or roll waves. The top of these disturbances is covered with a three-dimensional wave pattern. The thin base film, over which they move, is covered with slow-moving two-dimensional capillary waves. Primary entrainment occurs by the removal of the wavelets riding on top of the disturbance waves through a mechanism which is not yet established. Secondary entrainment can occur when droplets impinge on the film or when bubbles in the film burst free.

Two mechanisms have been identified for droplet deposition. Large droplets in small-diameter pipes are not influenced by gas-phase turbulence. The radial and circumferential components of their trajectory in the gas flow are largely determined by the initial velocity given to the droplets at their creation. Small droplets are influenced by gas-phase turbulence and may move through the gas phase by a diffusional mechanism. Progress has been made in discriminating between these two mechanisms, but this has not been translated into the development of a rate equation for droplet deposition. The droplets entrained in the gas may also coalesce, and this can affect their transport and deposition. Models of this process have shown some success in describing the changes in droplet size spectra.

Pressure drops in annular flow can be an order of magnitude larger than in a smooth tube at the same gas velocity. This is usually associated with the roughening of the film by waves, which scale with the film height. The film flow rate is known if the percentage of the liquid flowing as droplets is known. A relation between the film height and the film flow rate is usually obtained by assuming the film behaves the same as a single-phase turbulent flow. Entrained droplets can also influence pressure loss by changing gas-phase turbulence and by exchanging momentum with the liquid film.

Complications enter into the treatment of horizontal annular flows that are not present in vertical flows. Gravitational effects can cause both the liquid film and the droplets to distribute asymmetrically. Not much progress has been made in predicting the droplet distribution in the core, mainly because the relative importance of the trajectory and diffusional mechanisms for droplet dispersion is not known. Several mechanisms have been proposed to describe how a liquid film is maintained on the top portion of a horizontal pipe. These include droplet deposition, wave spreading and a secondary flow in the gas. The relative importance of these mechanisms, however, has not been defined.

Fundamental studies of annular flows have usually focused on vertical orientations in order to avoid asymmetries. For gas upflows at low velocities the liquid film can flow countercurrent to the gas. At very high gas velocities the gas shear causes the film to flow upward; the film behavior is the same as for a downflow under the same conditions. At intermediate gas velocities a very complicated film flow is observed, and the mechanism by which a film reverses its directions with increasing gas flow continues to be debated.

From the above discussion of the status of annular flow research, it is not surprising that participants in the Symposium focused on waves, drops and film behavior. However, the development of improved design methods was not neglected. It is now recognized that the performance of gas–liquid flows cannot be predicted by dimensional analysis or by correlations which ignore how the phases are distributed. Consequently, a question of prime interest was how to translate improved physical understanding of annular and dispersed flow into improved design equations.

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FLOODING IN TWO-PHASE FLOW: THE EFFECT OF TUBE LENGTH AND ARTIFICIAL WAVE INJECTION

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(*Received for publication* 2 *October* 1984)

Abstract—This paper investigates the phenomena of flow reversal and flooding, and in particular attempts to investigate the mechanism by which flooding occurs. A series of flow reversal air and water flow rates are presented, and these are found to be in good agreement with the findings of previous work. Flooding air and water flow rates are presented for a range of flow conditions and for three different lengths of tube. The flooding air flow rate is found to decrease as the tube length increases. This length effect has not always been observed in previous work, and a possible explanation is given in this paper. In order to examine the flooding mechanism a series of single and multiple wave injection experiments were performed. The resulting observations and measurements are consistent with the postulation that flooding occurs as a result of the growth of large-amplitude waves on the surface of the water film.

1. INTRODUCTION

1.1. *The phenomena of flooding and flow reversal*

Figure 1 illustrates the possible flow patterns assumed by a liquid following its introduction into a vertical tube in which a gas is flowing upwards. The liquid flow rate is constant, and the liquid is removed from the tube at positions both below and above that at which it is injected. At zero or low gas flow rates (1A) the liquid flows downwards as a film along the walls of the tube. As the gas flow rate is increased, the film becomes progressively more wavy, and as a consequence of this droplets of liquid are entrained into the gas core. Increasing the gas flow rate eventually causes a sudden change in the motion of the liquid film which allows some of the liquid to be transported above the point of liquid injection. The initial motion of the liquid above the point of injection may in some cases be in the form of droplets, but more importance is attached to the conditions at which the liquid begins to move upwards from its point of injection as a film along the walls of the tube. The phenomenon is called flooding (1B) and the gas flow rate at which it occurs is the flooding gas flow rate. As the gas flow rate is further increased (1C) and (1D) there is simultaneous motion of the liquid in both rising and falling films until ultimately (1E) all the liquid flows upwards, and the gas–liquid flow assumes the characteristics of vertical co-current annular flow. If now the gas flow rate is gradually reduced (1F) a point is reached at which the liquid begins to creep downwards from the point of injection, in the form of an agitated film which 'hangs' from the tube walls (1G). The phenomenon occurring at point (1G) is termed flow reversal, and the gas flow rate at which the hanging liquid film first appears is the flow reversal gas flow rate. As the gas flow rate is further reduced the downwards motion of the film depends on the wetting properties of the tube surface. Considerable reduction of the gas flow rate may be necessary to re-establish the simultaneous existence of both climbing and falling films (1H). Wallis [1] performed experiments which investigate the changes in gas flow rate necessary to cause the changes in flow pattern illustrated in Fig. 1.

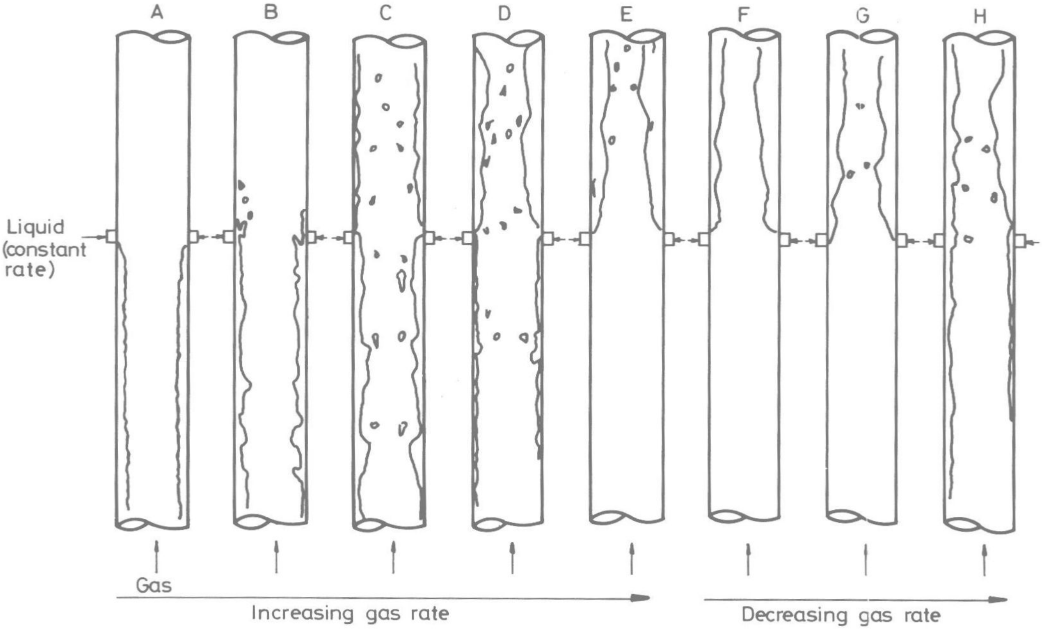

Fig. 1. Flooding and flow reversal.

The phenomena of flooding and flow reversal are of industrial importance. In the process industries vertical tube reflux condensers, for example, rely on the counter-current flow of vapour and condensate. The vapour flow rate must not be allowed to exceed that which would cause flooding, because this would result in undesirable carry-over of condensate. In the power industries, it is important to be able to predict the onset of flooding when consideration is given to the events which would follow a loss of coolant accident in a Pressurised Water Reactor. In this situation flooding limits the rate at which liquid can be supplied as emergency coolant at the top of the reactor core, because in some situations the rising vapour formed as a result of boiling at the surface of the reactor fuel rods would cause flooding, thus preventing the downwards flow of liquid into the reactor core.

1.2. *Theoretical and empirical treatments of flooding and flow reversal*

1.2.1. *Flow reversal correlations.* A widely used method for the prediction of flow reversal gas and liquid flow rates is that of Wallis [1]. In this method dimensionless superficial velocities are defined according to the equations:

$$V_g^* = V_g \rho_g^{1/2}[gD(\rho_l - \rho_g)]^{-1/2} \tag{1}$$

$$V_l^* = V_l \rho_l^{1/2}[gD(\rho_l - \rho_g)]^{-1/2}, \tag{2}$$

where V_g is gas superficial velocity (m/s), V_l is liquid superficial velocity (m/s), V_g^* is dimensionless gas superficial velocity (—), V_l^* is dimensionless liquid superficial velocity (—), ρ_g is gas density (kg/m^3), ρ_l is liquid density (kg/m^3), D is tube i.d. (m) and g is acceleration due to gravity (m/s^2).

Wallis suggested that the flow reversal transition occurs at a gas flow rate corresponding to a value of V_g^* of between 0.8 and 0.9. Puskina and Sorokin [2] proposed a correlation for flow reversal based on the Kutateladze stability criterion, which expresses a balance between inertial forces in the gas, buoyancy forces and surface tension forces. The equation presented is

$$K = V_g \rho_g^{1/2} [g\sigma(\rho_l - \rho_g)]^{-1/4}, \tag{3}$$

where σ is surface tension (N/m), K is Kutateladze number (—) and flow reversal occurs when $K = 3.2$.

Wallis and Makkenchery [3] compare the predictions of this equation with those of Wallis's [1] criterion, finding that whilst Wallis's criterion gives good predictions of the flow reversal gas flow rate in tubes of small diameter, the equation presented by Puskina and Sorokin [2] gives better predictions as the tube diameter increases above approximately 50 mm.

1.2.2. *Theoretical treatments of flooding.* The importance of flooding to the process and power industries has led to extensive research being performed with the aim of providing theoretical and empirical methods for the prediction of flooding gas and liquid flow rates. There are a large number of theoretical predictions and review of these is presented by Imura *et al.* [4]. Some of the more important treatments are listed and discussed below:

(1) Shearer and Davidson [5] gave one of the earlier theoretical treatments of flooding. They approached the problem by calculating the size and shape of a standing wave on a vertical liquid film. They assumed that the wave forms due to the presence of a Kelvin–Helmholtz instability resulting from the acceleration of the gas, and, using a force balance they derived a third-order differential equation relating the film thickness to the distance along the wave. The solution, which was obtained numerically, showed that the amplitude of the standing wave becomes large for some value of the gas flow rate. Shearer and Davidson claimed that this value of the gas flow rate should be used to determine the flooding gas flow rate.

(2) Schutt [6] gave another theoretical treatment, which suggested that the flooding transition occurs primarily as a result of interfacial shear, the effects of which are completely neglected by Shearer and Davidson [5]. However, the treatment given by Schutt has since been shown to be of doubtful validity, because it has been proved that the interfacial shear is insufficient to be the single cause of the creation of the climbing liquid film at the flooding point. (See Hewitt *et al.* [7].)

(3) Cetinbudalkar and Jameson [8] provided an analysis which assumes that flooding occurs when the gas velocity is sufficient to cause the formation of infinitesimally small waves on the surface of the liquid film.

(4) Moalem Maron and Dukler [9, 10] have given consideration to three possible mechanisms by which flooding may be initiated:

(4a) The first of these involves the calculation of the gas velocity necessary to support a droplet of liquid in the gas core. The resulting equation is coincidentally of the same form as equation (3). However, in arriving at this form of equation the authors assumed that a droplet entrained from the film undergoes a gradual acceleration as it moves into the gas core. The gas core velocity is typically 10 m/s, so it must be considered unlikely that the droplet would actually undergo a gradual acceleration.

(4b) The second mechanism postulated is that flooding occurs as a result of the film switching between different stable states, some of which result in upwards motion of some part of the film.

(4c) The final suggestion made by Moalem Maron and Dukler [9] is that the flooding conditions may be found by calculation of the gas flow rate at which the speed of downwards propagation of a kinematic liquid wave becomes zero. The calculations made by Moalem Maron and Dukler [9] on the basis of suggested mechanism (4b) require the assumption that the water film flow is laminar, and although the mechanism suggested in (4c) is general, the solution given by Moalem Maron and Dukler [9] also requires a laminar water film. However, observations close to the flooding point clearly indicate that the liquid film is turbulent.

1.2.3. *Empirical flooding correlations.* A widely used semi-empirical method for calculating flooding gas and liquid flow rates has been presented by Wallis [1, 11] and Hewitt and Wallis [12]. This method uses the dimensionless superficial velocities evaluated in equations (1) and (2). Wallis postulates that the flooding transition may then be represented by an equation of the form:

$$(V_g^*)^{1/2} + (V_l^*)^{1/2} = C, \tag{4}$$

where C is a constant whose value is determined by the conditions of liquid entry to the tube or channel, and V_g^* and V_l^* are the dimensionless gas and liquid superficial velocities as defined in equations (1) and (2). Smooth liquid entry and exit may be provided by the use of small sections of porous tube wall made of sintered bronze as described by Hewitt *et al.* [7]. For these conditions the value of C is found empirically by Hewitt and Wallis [12] to be between 0.88 and 1.00. The above correlation has been modified by Wallis [13] to predict the flooding point for viscous liquids, the revised equation being:

$$(V_g^*)^{1/2} + A(V_l^*)^{1/2} = C, \tag{5}$$

where A and C are both constants which vary with the viscosity of the liquid. Another set of correlations have been based on the Kutateladze stability criterion. An example of such a correlation is that of Puskina and Sorokin [2]. The equation given is:

$$V_g = 3.2[g\sigma(\rho_1 - \rho_g)/\rho_g^2]^{1/4}, \tag{6}$$

where all the symbols have been defined previously.

1.2.4. *Discussion of flooding correlations.* Despite the large number of methods which are available to calculate flooding conditions, predictive success is limited. The empirical correlations usually fail to work for geometries or fluids other than those which were used to develop them, and the theoretical correlations provide a wide range of predictions, and further suggest a range of trends as, for example, the gas flow rate is increased. Perhaps one of the major reasons for this lack of success is the lack of understanding or agreement concerning the mechanism by which flooding occurs. As has been indicated above, several different mechanisms have been postulated, but none of the resulting equations is able to predict accurately flooding conditions. Further confusion has been caused by the diverse methods which have been used to supply and remove the liquid film. The flooding gas and liquid flow rates are known to be sensitive to the entry and exit conditions. Imura *et al.* [4] and Hewitt *et al.* [7] reviewed the available inlet and outlet geometries, and Hewitt *et al.* [7] concluded that porous sections of tube, carefully matched to the main tube, provide the closest approximation to the ideal of smooth liquid injection and removal. Using this arrangement, Hewitt *et al.* [7] found the flooding gas flow rate is strongly affected by the length of tube between the liquid inlet and outlet sinters, with the flooding gas flow rate decreasing as the length of the tube increases. This effect was confirmed by Chaudry [14]. Imura *et al.* [4] performed a number of experiments on flooding in vertical tubes. They produced a complicated semi-empirical correlation based on their results, and claimed that the results of Hewitt *et al.* [7] could be correlated using their equation. Close examination, however, reveals that this is not so. Other investigations, for example by Grolmes *et al.* [15], and more recently by Smith *et al.* [16], have not observed a length effect. This is possibly because the liquid exit geometries used by the above investigators lead to a localisation of the flooding phenomenon at the liquid exit, so that flooding is initiated by the flow conditions at the liquid exit, and no length effect would be expected. Hewitt *et al.* [7] interpreted the observed length effect as an indication that flooding occurs as a result of wave growth in the falling liquid film. They claimed that for given liquid and gas flow rates, waves which have not grown sufficiently by the time they are extracted after falling through a short distance, can in longer tubes grow to a size which enables them to in some way initiate the flooding event. Moalem Maron and Dukler [9] disagreed, concluding from the results of Smith *et al.* [16] that flooding occurs either as a result of the film switching between different states, or as a result of the speed of propagation of a kinematic liquid wave tending to zero. Moalem Maron and Dukler [9] did not give any consideration to the possibility that the film removal geometry used by Smith *et al.* [16] might, as discussed above, remove the length effect.

1.3. *The aims of the present work*

The main aim of the present work is to investigate the hypothesis that the flooding phenomenon occurs as a result of the growth of liquid waves on the surface of the falling liquid film. It records a series of flow reversal air and water flow rates, and further records flooding air and water flow rates at three different pressures and for three different lengths of tube between the water inlet and outlet sinters. Finally, the effect of injecting artificial water waves into the film is investigated. Single waves were injected using a hand-operated hypodermic syringe, and multiple waves were injected using a method described by Azzopardi and Whalley [17].

2. EXPERIMENTS

All measurements were made with air and water flowing in a transparent acrylic resin tube of 0.032 m i.d. The tube used was of the same type and diameter as that used by Wallis [1], Hewitt and Wallis [12] and Hewitt *et al.* [7], thereby enabling a direct comparison to be made between the findings of these authors and those of the present work.

2.1. *Flow reversal experiments*

The experimental arrangement used to investigate flow reversal is shown schematically in Fig. 2. The air was introduced to the bottom of the tube and flowed alone along the tube for a calming length of 3.0 m, before coming into contact with the water film, which was introduced to the tube through a short length of porous wall made from sintered bronze. To ensure an even distribution of water around the periphery of the tube, the water was supplied to the sinter unit through four inlets, equally spaced around the outer wall of the sinter unit. The mixture of water and air leaving the top of the test section was returned to the water storage vessel, where the air was vented to the atmosphere.

The flow reversal experiments were conducted in the manner described by Wallis [1]. A high air flow was used to drive all the water from the region of the tube below the water inlet section, effectively drying the tube walls. The water flow rate and the tube pressure were then set at the required values. The air flow rate was then slowly reduced whilst adjustment of the valve at the top of the tube enabled the pressure to be maintained at the required value. At some air flow rate the agitated hanging film described in the introduction and by Wallis [1] appeared below the water inlet. The value of the air flow rate was that used as the flow reversal air flow rate, although considerable further reduction of the air flow rate was necessary to initiate a true falling film. The hanging film definition of flow reversal was used

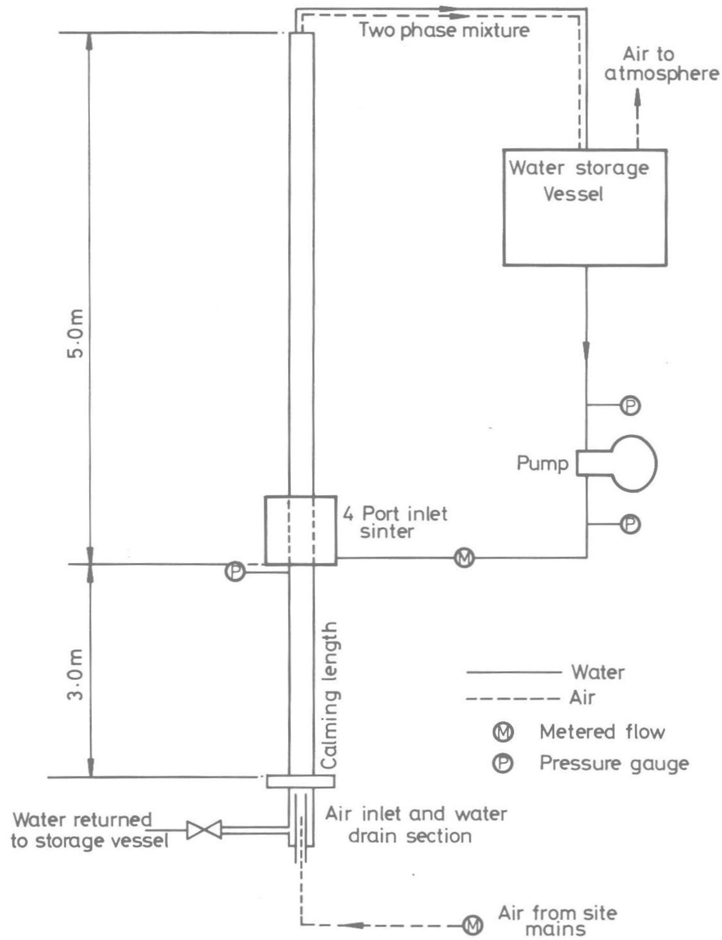

Fig. 2. Experimental arrangement for flow reversal investigations.

for two reasons: first, to be consistent with the definitions of other investigations, and second, because results obtained from measuring the air flow rate at which the hanging film became a true falling film were somewhat subjective and showed a large amount of scatter. During the course of the experiments it was also observed that any trace of wetness in the region of the tube just below the liquid inlet caused flow reversal at gas flow rates considerably higher than for a completely dry tube. Again these flow rates were widely varying and not reproducable. Flow reversal measurements were made for six water flow rates and for six pressures.

2.2. *Flooding experiments*

The experimental arrangement used to investigate flooding is shown in Fig. 3. The water film was introduced to the tube through the top sinter. This sinter had one water supply port. The water film was removed from the tube through a second sinter section, after flowing downwards through the required length of tube. The sinter section used to remove the water from the tube had four water outlet ports. Earlier measurements had been made using a film removal sinter section with a single outlet port. This proved to be unsatisfactory because in

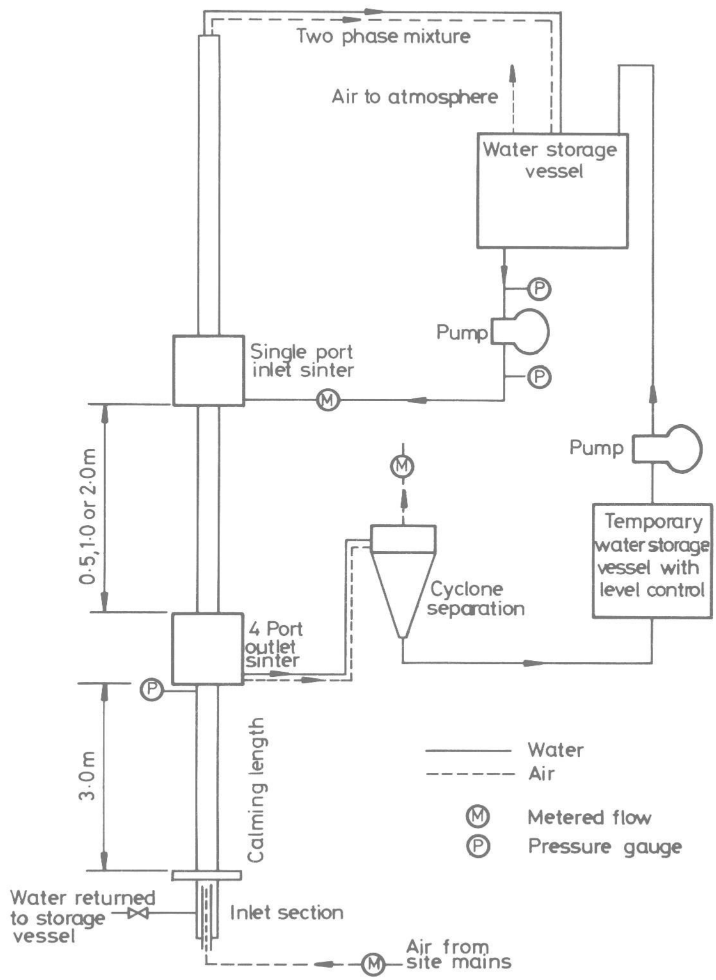

Fig. 3. Experimental arrangement for flooding investigations.

order to remove the liquid film completely it was necessary also to remove an appreciable proportion (up to 50%) of the air flowing upwards in the tube. The flooding air flow rate was calculated by subtracting the air removed at the outlet sinter from the total air flow rate, and therefore errors would have been introduced by the need to subtract one large flow rate from another. Furthermore, the removal of a large amount of air with the water film would be likely to cause turbulence in the region of the liquid outlet sinter. Changing to the sinter with four outlet ports enabled all of the water film to be removed from the tube whilst reducing the total air flow rate by between 0.5% and 8.0%. This improvement was apparently because the increased area for flow removal presented by four outlet ports changed the outlet flow from a slug flow to a stratified flow. The two-phase mixture removed at the outlet sinter was separated in a cyclone, the water being returned to the storage vessel and the air being metered using a gas meter. The small amount of air thus removed was subtracted from the total air flow in the tube. For high liquid flow rates and longer test sections the water film was particularly wavy at the flow removal sinter. Under these conditions small amounts of water were not removed and fell through the air calming length to the bottom of the tube. The design of the air inlet (see Fig. 3) ensured that any water reaching the bottom of the tube would not interfere with the incoming air, and further that a build-up of water could be prevented by occasionally opening the drain valve.

The experimental procedure was first to establish the required water film flow rate and tube pressure. The valve controlling the removal of the water film was then adjusted so that the water film could be completely removed, accompanied by as little air as possible. The flow rate of the removed air was then measured using a gas meter. The total air flow rate was then increased in small increments whilst using the valve at the top of the tube to maintain the pressure at the required value. At low water flow rates flooding was slow to develop, so care had to be taken not to overshoot the flooding air flow rate. The flooding air flow rate was found to be sensitive to small changes in the tube pressure, which therefore had to be carefully maintained at the required value. The flow rate of the air removed with the water film was not affected by changes in the total air flow rate.

At some value of the total air flow rate flooding of the water film occurred. Flooding was observed to begin with the appearance of a highly disturbed region of the water film, usually at or near the water removal sinter. This disturbed region propagated up the tube with a speed which increased with increasing water flow rate. Its propagation caused the appearance of further regions of disturbance, and the eventual propagation of one such region above the liquid inlet sinter signalled the onset of flooding. Flooding flow rates were recorded for three different lengths of tube between the water inlet and outlet sinters, for three pressures and for 10 water flow rates.

2.3. *Wave injection experiments*

2.3.1. *Single wave injection.* The experimental arrangement used to investigate the effects of wave injection was similar to that for the flooding experiments (Fig. 3) with modifications as shown in Fig. 4. For all of these experiments the distance between the water inlet and outlet sinters was 2.1 m. Three different positions of the wave injection sinter were used, as shown in Fig. 4. The wave was injected using a graduated plastic syringe.

It was considered possible that the addition of the wave injection sinter section to the apparatus might cause some disturbance of the water film, consequently causing a change in the flooding gas flow rate. As a check the flooding experiments were repeated with the wave injection sinter in each of the three possible positions. As will be shown in the results, the flooding gas flow rates were not affected. The experimental procedure for the wave injection experiments was to establish the falling water film first, as in the flooding experiments. The flooding air flow rate was measured, and then the falling film flow was re-established. The air flow rate was then set at some value, and subtraction of this value from the flooding air flow rate gave a measure of the amount by which the gas flow rate was lower than the flooding gas flow rate. Then if X is total air flow rate at flooding (kg/s), Y is chosen total air flow rate (kg/s), Z is air take-off flow rate at outlet sinter (kg/s), and W is amount by which air flow rate is less than flooding air flow rate (kg/s), then

$$W = (X-Z)-(Y-Z) \tag{7}$$

$$W = X-Y. \tag{8}$$

It was therefore unnecessary to measure the take-off air flow rate. The wave injection syringe was filled with water from the water film, and some time was allowed for the disturbance thus caused to be removed from the system. A chosen amount of water was then injected into the flow and the results observed. If the injection of the wave caused a disturbance in the film flow, the nature of the disturbance was recorded, and the approximate position of the initiation of the disturbance was recorded using graduations drawn on the tube walls.

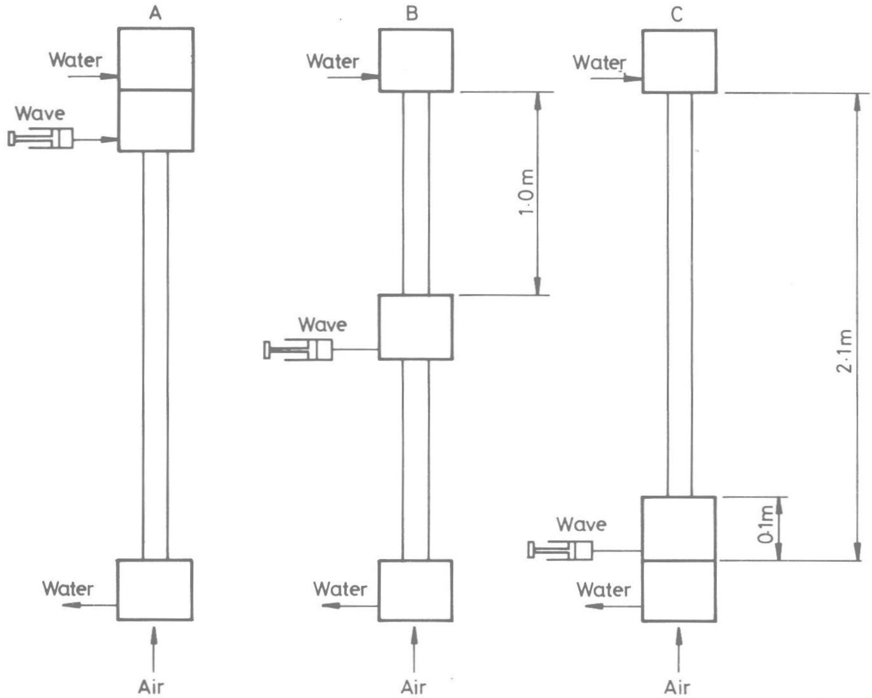

Fig. 4. Experimental arrangement for wave injection investigations.

Detailed discussion of the observations is given in the results. Wave injection experiments were performed at a tube pressure of 2.0 bar and for two water flow rates and three wave injection positions.

2.3.2. *Multiple wave injection.* The experiments to investigate the effect of multiple wave injection again used a graduated plastic syringe to inject waves into the falling film. The mechanical mechanism used to inject the waves is described by Azzopardi and Whalley [17]. The use of this system enabled close control of the rate of wave injection. One-way valves were used to allow water to be supplied to the syringe from a separate storage vessel, thus avoiding the depletion of the falling water film prior to each wave injection. The total flow rate of the falling water film was therefore the sum of the flows provided by the water inlet sinter and by the wave injection sinter. The multiple wave injection experiments sought to investigate the effect on the flooding air flow rate of varying the proportion of a given water flow rate which was supplied to the tube in the form of artificial waves. The experimental procedure was first to find the flooding air flow rate for a given water flow rate supplied entirely through the water film inlet sinter. The air flow rate was then reduced to re-establish the falling water film. The wave injection system was set to deliver the required rate of injection, and the water film flow rate reduced so that the total rate of water supply to the tube remained unchanged. The air flow rate was then increased until flooding occurred, and the flooding air flow rate recorded. The experiments were performed with the wave injection sinter immediately below the water film inlet sinter (Fig. 4A), at a pressure of 2.0 bar, and for water flow rates of 37.8 g/s and 88.2 g/s. All the waves injected into the film flow contained 5.0 g of water.