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LOW AND HIGH HEAD FLOODING FOR COUNTERCURRENT FLOW IN SHORT HORIZONTAL TUBES

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Abstract—Experiments have been carried out discharging water along a horizontal 50 mm bore tube against a countercurrent flow of air. With the water flowrate constant, the air flowrate was slowly increased until waves appeared, restricting the outflow of water. This defined the low head flooding condition which was found to be in good agreement with previous theory for low water discharge rates. A new treatment gives good agreement over the whole experimental range. Once the low head flooding set in, the water head built up in the water supply tank connected to the horizontal tube and the air flowrate had to be reduced substantially below that required for the initiation of flooding before the water discharge rate was fully reinstated. This is the high head flooding condition and experimental results are in substantial agreement with those of others. Previous theory for high head flooding is derived in a simpler fashion and related to the Kelvin–Helmholtz instability criterion. The theory is shown to be a generalization of the criterion.

1. INTRODUCTION

Flooded discharge of water from a vessel and along a short horizontal tube (length/diameter ratio of approx. 10) with a counterflow of air has been studied experimentally by Richter *et al.* (1978), Krolewski (1980) and Gardner (1983). Similar flooded discharge of carbon dioxide against air and brine against water has been studied by Leach & Thompson (1975) and Mercer & Thompson (1975). A feature of most of this work was that the inlet of the horizontal tube from the vessel containing the denser fluid was well-submerged and there was free discharge of the denser fluid from the other end of the tube. The discharge rate of the denser fluid is then only a function of the flowrate of the lighter fluid and is independent of the dense fluid's depth in its supply vessel. The term "high head flooding" will be used to describe this type of flooding.

Krolweski (1980) showed that, if one sets a water flowrate and then slowly increases the air flowrate, a flooding condition may be achieved with a much higher air flowrate than applicable to high head flooding. In this condition the dense fluid in its supply tank does not cover the entry to the horizontal tube, though free discharge of the dense fluid from the other end of the tube is still allowed, and the term "low head flooding" can be applied.†

Krolewski further showed that, once a low head flooding condition has been obtained, the air flowrate has to be reduced to the value for high head flooding for the water discharge rate to attain its original value. The occurrence of low head flooding prevents the discharge of all the water being supplied and the head of water in its supply vessel builds up.

The present paper reports work similar to that of Krolewski but with a simpler configuration, so that the results are amenable to theoretical interpretation. Krolewski's water supply vessel was connected to a 50.8 mm bore horizontal tube by a 250 mm long demountable section, also 50.8 mm bore. In some cases the connecting tube was vertical, when little difference was found between low and high head flooding. In other cases it sloped at 45% and then there was a pronounced difference between the two kinds of flooding and, at least in the case of low head flooding, it is to be expected that acceleration of the water down the sloping pipe could affect the flooding condition. In the present experiments the horizontal tube connected directly to the large water supply vessel.

†A referee noted that two papers (Siddiqui *et al.* 1986; Ardron & Banerjee 1986) concerning low head flooding in long horizontal tubes have been published recently in this journal. A comment on this work is given in the Appendix.

Reference has usually been made to Wallis' (1969) flooding theory but Gardner (1983) showed that, overall results for high head flooding agreed better with a treatment, which, it will be shown later in this paper, is related to the Kelvin–Helmholtz instability criterion. The agreement is not perfect, which may be due to a number of factors but, most important, is the oscillatory nature of the flow, which is sometimes called "glugging". The severity of glugging tends to decrease with increased light-phase flowrate and probably decreases as the densities of the two phases approach each other.

The system is essentially steady as the low head flooding condition is approached in the manner described above and better agreement may be expected with theoretical treatments. Indeed, it will be shown that Wallis' (1969) theory can be regarded as applicable when the water flowrate is low and the air flowrate is high but a treatment will be given which agrees with the experimental results over the whole range.

2. THE EXPERIMENT

2.1. *Apparatus and experimental method*

The apparatus is shown schematically in figure 1. There are two identical vessels with a diameter of 300 mm and height of 1000 mm. They are connected by a horizontal tube, which is 500 mm long and has a bore of 50 mm. Vessels and the tube are standard process plant glass fittings. Thus there are 50 mm bore stubs integral with the vessels and the horizontal pipe is connected to the stubs with the usual ring-flanges but care was taken to ensure that there was no internal lip at the joints. The entry of the tube to the vessels was rounded, as is characteristic with such glass equipment.

Metered water was supplied to the bottom of one vessel and was discharged from the base of the other. There was a similar supply of metered air through the top of one vessel and out of the top of the other to provide a countercurrent flow. Air and water temperatures were measured with both vessels operating at nominally atmospheric pressure.

A steady flow of water was supplied to the system and the events in the horizontal tube were observed as the air flowrate was increased by small increments. The flow was quiet and steady until, at a well-defined air flowrate, waves appeared upon the interface and travelled in the direction of the air flow, thus restricting the discharge of water and causing the level in the tank to start increasing with time. This defined the low head flooding condition.

When the tube was initially less than half full of water and higher air flowrates obtained, the waves appeared all along the tube. With the tube initially more than half full of water, increasing air flow caused the water level at inlet to increase sufficiently to allow the waves to bridge the tube and the onset of the glugging phenomenon was evident. Once the latter condition occurred, the depth in the water supply tank increased continuously until the air flow was reduced.

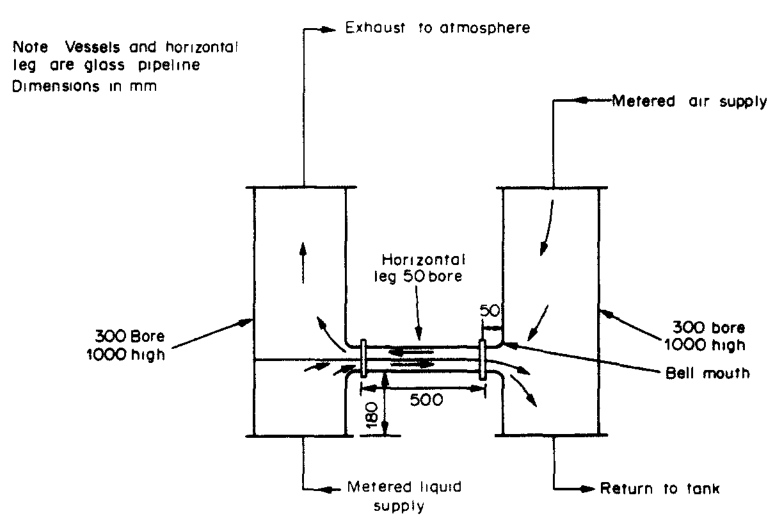


Figure. 1. Layout of the apparatus.

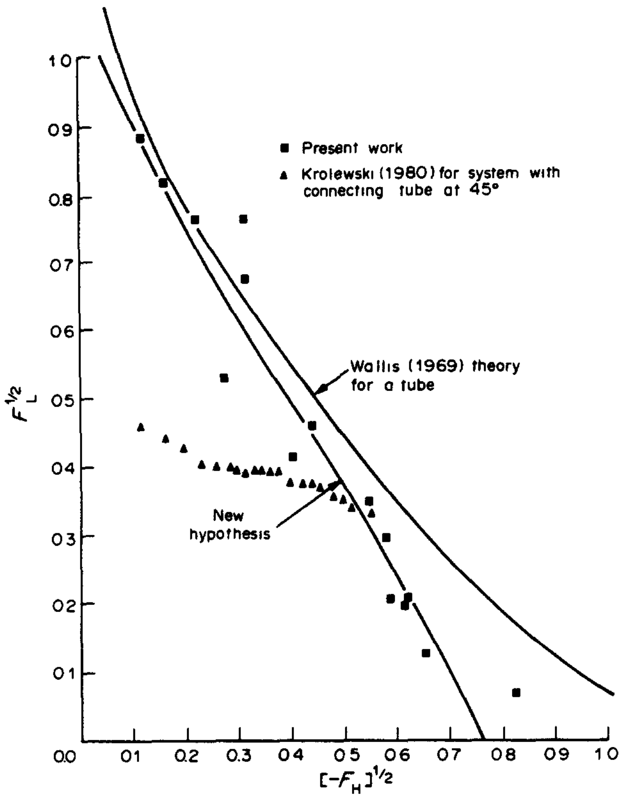


Figure. 2. Comparison of experimental low head flooding results with theory.

For the lowest water level, the water discharge was completely prevented and the water level sloped gently upwards from the air inlet to the air discharge. At intermediate levels, the waves tending to form at the water inlet did not quite bridge the tube. Spray formed at their crests.

Most of the measurements were made in the manner described above. Sometimes, however, the water was allowed to build up in the water supply vessel after low head flooding set in and then the air flowrate was slowly reduced by small increments. Sufficient time was allowed between increments to see if the level in the water supply tank varied with time. When the level was steady, it was assumed that high head flooding obtained and the air and water flowrates were noted.

2.2. *Results*

The low head flooding results are plotted in figure 2. The coordinates are $F_L^{1/2}$ and $(-F_H)^{1/2}$, where

$$F_L = \left(\frac{\rho_L}{\Delta\rho g L}\right)^{\frac{1}{2}} v_{LS}, \text{ and } F_H = \left(\frac{\rho_H}{\Delta\rho g L}\right)^{\frac{1}{2}} v_{HS} \qquad [1]$$

where ρ_L and ρ_H are the densities of the light and heavy phases, $\Delta\rho$ is the density difference between the phases, g is the acceleration due to gravity and L is the characteristic dimension of the channel cross-section which, in this case, equals the tube diameter, D; L will usually be chosen to be the depth of the channel; v_{LS} and v_{HS} are the superficial velocities of the light and heavy phases, which are the flowrates divided by the cross-sectional area of the tube. The air flow direction is taken to be positive.

Figure 3 gives the experimental results for high head flooding in the same coordinates and they are seen to lie within the scatter of results of other workers. In this respect, the wide range of entry conditions to the horizontal pipe are to be noted. Krolewski's (1980) entries are described in the Introduction. Richter *et al.*'s (1978) entry was similar, while Gardner (1983) used a direct connection to a vessel but it projected through the vessel wall and both sharp-edged and bell-mouthed entries were employed.

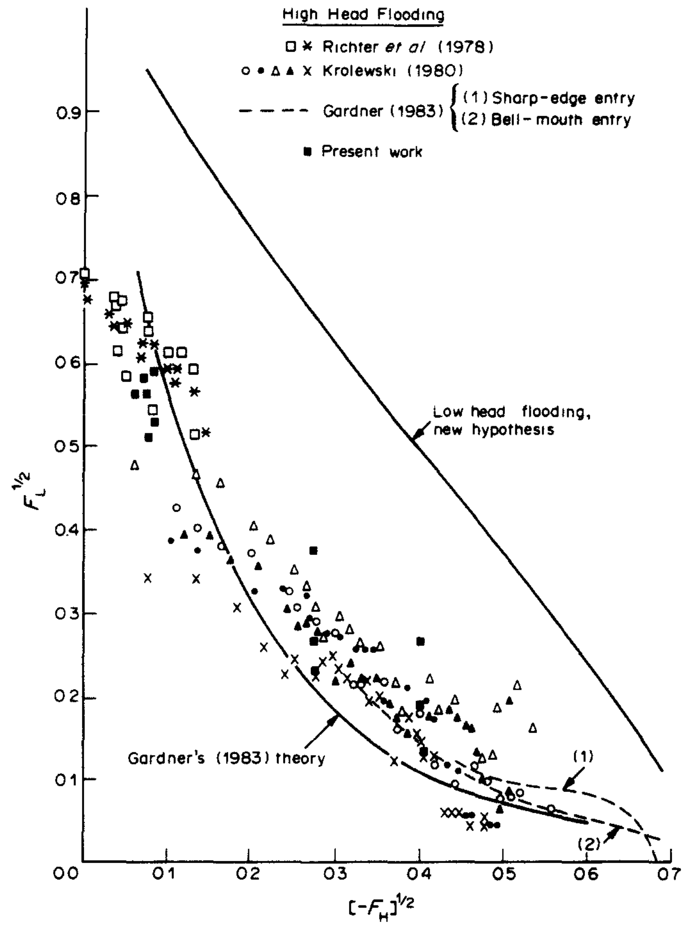


Figure. 3. Comparison of high head flooding results.

A curve based upon a new hypothesis for low head flooding, which will be described in section 3.1, is transposed from figure 2 to figure 3 and large difference between low and high head flooding is evident.

3. THEORY

3.1. Wallis' (1969) theory

Wallis (1969) derived the expression

$$(-F_H)^{\frac{1}{2}} + F_L^{1/2} = 1 \tag{2}$$

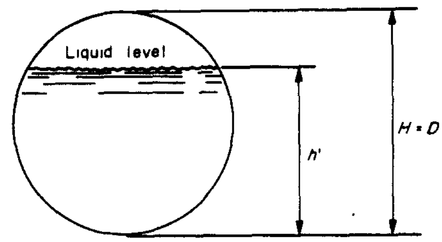
as the condition for flooding in a rectangular channel. Here the characteristic cross-section dimension, L, equals the channel depth. A derivation applicable to a channel of arbitrary cross-sectional shape will now be given.

Wallis started from the first-order approximation to the dynamic equation for a solitary wave in a rectangular channel, given by Long (1956). This is essentially the equation giving conditions for a stationary small disturbance, which, in general, is

$$\frac{F_H^2}{A^3} + \frac{F_L^2}{(1-A)^3} = \frac{k}{W}, \tag{3}$$

as given by Gardner (1977). A is the fraction of the tube's cross-sectional area that is occupied by the heavy phase and

$$W = \frac{w}{L}, \tag{4}$$



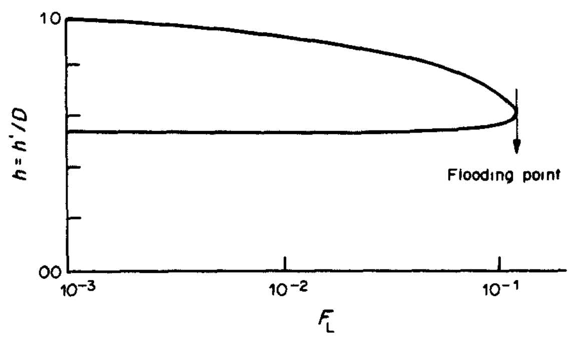


Figure. 4. Variation of relative depth with F_L for critical flow in a tube when $F_H = -0.36$.

where w is the width of the interface and k is defined by

$$A' = kL^2, \tag{5}$$

where A' is the cross-sectional area of the duct. It may be noted that the r.h.s. of [3] simply becomes unity in the case of a rectangular channel where L is equated with the channel depth.

Equation [3] can be employed to follow the experiments described in the last section. The heavy-phase flowrate and thus F_H is set. The light-phase flowrate or F_L is slowly increased. Figure 4 gives a typical result for a tube in terms of

$$h = \frac{h'}{D}, \tag{6}$$

where h' is the depth of the heavy phase, vs F_L. It is seen that [3] cannot be satisfied if F_L exceeds a certain value and this maximum value was chosen by Wallis for his flooding criterion. Equation [3] is therefore differentiated with respect to h, with F_H held constant, and dF_L/dh is set equal to zero to obtain an equation to solve simultaneously with [3]. This process is the same as differentiating with respect to h with both F_H and F_L held constant.

The result obtained for a rectangular channel is [2]. The result for a tube does not have a simple analytical form but is given in figure 2. It must be emphasized, because it does not usually appear to be appreciated, the [3] must also be satisfied. This is so in the reported experiments concerning the free discharge of the heavy phase.

3.2. A new hypothesis for low head flooding

The first observation that was made in attempting to formulate a theoretical description of low head flooding was that a long bubble is held stationary, according to Benjamin (1968), in a horizontal tube if $(-F_H)^{1/2} = 0.736$. Consideration of surface tension for the 50 mm bore tube employed reduces this value to 0.68, according to Gardner & Crow (1970), and, if this value is plotted for $F_L^{1/2} = 0$ in figure 2, it is a possible extrapolation of the low head flooding results. However, no way could be found to extrapolate the long-bubble conditions to allow for flow of light phase from the bubble over a heavy-phase surface, which was separated from the top wall of the tube. Part of the reason for this is that the long bubble changes rapidly in form once it reaches

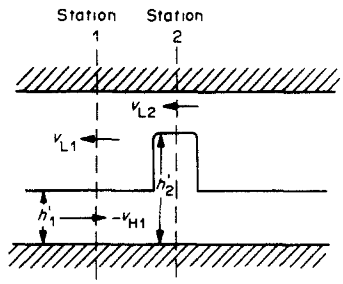


Figure. 5. Definition sketch for low head flooding hypothesis.

the light-phase discharge end of the tube. Another reason may be that the heavy-phase flow beneath the bubble is supercritical and critical discharge obtains in the experiment prior to low head flooding.

The model proposed here is illustrated in figure 5. It considers a stationary disturbance set up on the critical flow and supposes that its height compared to its length in the streamwise direction is sufficiently large that the heavy-phase flow does not enter it substantially, except to cause its growth. Therefore it grows until the heavy phase at the top of the disturbance is a stagnation point. The light-phase flow will, of course, exert a force on the disturbance to move it in the light-phase flow direction but it is assumed that growth can occur before the disturbance accelerates appreciably.

It is next assumed that the resultant disturbance, which will now be substantial, will be stable if the light-phase flowrate above it is critical for a staionary small disturbance and, finally, the light-phase flow from the top of the disturbance upstream will suffer energy losses as for a sudden expansion.

Referring to figure 5, station 1 is located in the basic critical flow streams on the heavy-phase inlet side of the disturbance and station 2 is in the disturbance. The heavy-phase flow depth is h′, v is the velocity, p is pressure at the interface, A' with a subscript is the cross-sectional area of the heavy phase, A' without a subscript is the cross-sectional area of the channel and ρ is density. Subscripts 1 and 2 denote the station and subscripts L and H denote light and heavy phases, respectively.

At station 1 critical flow is obtained, so that

$$\frac{F_{\mathrm{H}}^2}{A_1^3}+\frac{F_{\mathrm{L}}^2}{(1-A_1)^3}=\frac{k}{W_1}. \qquad [7]$$

At station 2 there is critical flow with no heavy-phase velocity, so that

$$\frac{F_{\mathrm{L}}^2}{(1-A_2)^3}=\frac{k}{W_2}. \qquad [8]$$

An energy balance on the heavy phase (i.e. Bernoulli's equation) is

$$\tfrac{1}{2}\rho_{\mathrm{H}}v_{\mathrm{H1}}^2+p_1+\rho_{\mathrm{H}}gh'_1=p_2+\rho_{\mathrm{H}}gh'_2. \qquad [9]$$

A momentum balance is written for the light phase in the usual fashion for a sudden expansion. Thus it is assumed that the pressure p_2 is obtained over the whole of the area $(A'-A'_1)$ just downstream of the disturbance in the light-phase flow direction:

$$\rho_{\mathrm{L}}v_{\mathrm{L2}}^2(A'-A'_2)+p_2(A'-A'_1)+\rho_{\mathrm{L}}g(h'_2-h_1)(A'-A'_1)=\rho_{\mathrm{L}}v_{\mathrm{L1}}^2(A'-A'_1)+p_1(A'-A'_1). \qquad [10]$$

The first terms on each side of [10] are momentum fluxes and the remaining terms are pressure forces. The third term on the l.h.s. of [10] is a correction for the difference in levels at which p_1 and p_2 are defined.

(p_1-p_2) is eliminated between [9] and [10] and the continuity equation is applied to achieve

$$\frac{F_{\mathrm{H}}^2}{2A_1^2}+\frac{(A_2-A_1)F_{\mathrm{L}}^2}{(1-A_1)^2(1-A_2)}=h_2-h_1. \qquad [11]$$

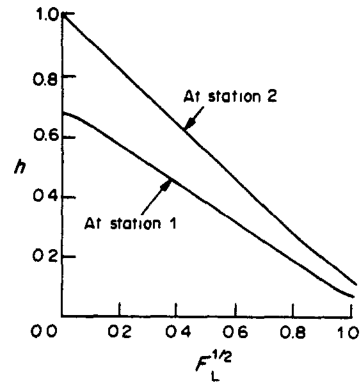


Figure. 6. Theoretical fractional depths for low head flooding in a tube.

Equations [7], [8] and [11] are solved simultaneously to give F_L as a function of F_H. The result for a tube is given in figure 2 and is seen to be in excellent agreement with the experimental results over the whole range. Figure 6 gives the estimated values of h_1 and h_2.

3.3. *High head flooding*

The theory for high head flooding, which gives rise to the theoretical line in figure 3, can be put in a simpler form than that given by Gardner (1983), although the final result is the same, and thus be related to the Kelvin–Helmholtz instability criterion.

The velocity, v_w, of a small disturbance can be determined by modifying [3]:

$$\frac{1}{A}\left(\frac{F_H}{A} - PV\right)^2 + \frac{1}{(1-A)}\left[\frac{F_L}{(1-A)} - V\right]^2 = \frac{k}{W}, \qquad [12]$$

where

$$V = \left(\frac{\rho_L}{\Delta\rho g D}\right)^{\frac{1}{2}} v_w \qquad [13]$$

and

$$P = \left(\frac{\rho_H}{\rho_L}\right)^{\frac{1}{2}}. \qquad [14]$$

Expansion of [12] gives

$$\left[\frac{P^2}{A} + \frac{1}{(1-A)}\right]V^2 - 2\left[\frac{PF_H}{A^2} + \frac{F_L}{(1-A)^2}\right]V + \frac{F_H^2}{A^3} + \frac{F_L^2}{(1-A)^3} - \frac{k}{W} = 0 \qquad [15]$$

and it is seen that a stationary small disturbance, as given by the last three terms on the l.h.s. of [15], is associated with a moving small disturbance. This is merely the expression of the common knowledge of hydraulic engineers. However, the second disturbance will be simultaneously stationary if

$$\frac{PF_H}{A^2} + \frac{F_L}{(1-A)^2} = 0. \qquad [16]$$

Simultaneous solution of [3] and [16] gives the conditions for high head flooding, previously given by Gardner (1983):

$$F_H = -\left(\frac{k}{W}\right)^{\frac{1}{2}} \frac{A^2}{[A + P^2(1-A)]^{\frac{1}{2}}} \qquad [17]$$

and

$$F_L = \left(\frac{k}{W}\right)^{\frac{1}{2}} \frac{P(1-A)^2}{[A + P^2(1-A)]^{\frac{1}{2}}}. \qquad [18]$$

Now, if a rectangular channel is considered, [15] simply reduces to the controlling equation for the wave velocity of a long wave, as given by the Kelvin–Helmholtz analysis. The solution for V contains a square-root term and the analysis asserts that the argument of this term set equal to zero provides the condition of neutral stability. There are then two equal values of V, just as determined by the procedure used to obtain [17] and [18]. However, a more general result, which is applicable to a channel of arbitrary cross-section, has been obtained.

4. DISCUSSION

A distinction has been made between low and high head flooding. A system may operate with discharge of a given flowrate of a heavy phase along a horizontal pipe and against an increasing countercurrent flow of a light phase until the flowrate of the light phase reaches a certain value, giving the low head flooding condition. The discharge rate of the heavy phase then falls and a head builds up in its supply vessel. In most cases the same discharge rate cannot then be obtained until the light-phase flowrate is reduced substantially below its previous value; the new conditions are those of high head flooding.

A simple system of a horizontal pipe connected directly to a heavy-phase supply vessel has been studied experimentally and the low head flooding results are shown to be consistent with a postulated model, which, however, must be accepted with some caution. Agreement is good without the employment of any disposable constants. Nonetheless, such agreement in this system, in which the events are rapidly developing with time, may be fortuitous.

More complicated systems, in which the horizontal pipe has been connected to the heavy-phase supply vessel by a further section of sloping or vertical pipe, have been studied by Krolewski (1980). Figure 2 shows some of her results for low head flooding with a connecting pipe sloping at 45° and, not surprisingly, there is a substantial difference between those results and the present work. They are, nonetheless, seen to lie well above the high head flooding condition. On the other hand, when the connecting pipe was vertical, Krolewski found little difference between high and low head flooding. Also, it appears that the high head flooding condition is not very sensitive to heavy-phase inlet conditions that have been employed by various workers.

Lastly, it must be stressed that all the low head flooding experiments have employed essentially free-discharge conditions for the heavy phase from the end of the horizontal pipe.

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APPENDIX

Comments on Papers by Siddiqui et al. *(1986) and Ardron & Banerjee (1986) Recently Published in this Journal*

It is desirable to draw attention to the valuable contents of these papers. They study the onset of flooding when discharging water freely from the end of a horizontal pipe with a large length/diameter ratio against a slowly increasing countercurrent air flow. In the terminology of the present work, low head flooding was examined and no high head flooding was noted.

The end of the horizontal pipe at which water entered was continued in the air flow direction through either a mitred or a swept bend to a vertical pipe, at a point up with the water was introduced and the air was discharged. The system with a mitred bend resembles some of the systems studed by Krolewski (1980) but Krolewski obtained flooding with much smaller air flowrates. Details such as the exact nature of the bend, the manner in which water was introduced and the height of water introduction must influence the results. The system with a swept bend bears a superficial resemblance to Krolewski's systems in which a pipe sloping at 45° to the horizontal supplies water and discharges air. The results obtained are then of comparable magnitude to Krolewski's.

The papers emphasize the increase of water level due to friction from the water discharge to the other end of the horizontal pipe. They develop a simple empirical correlation between the higher liquid level and the gas flowrate and thus obtain a method for prediction of flooding which stresses the length of the horizontal pipe. It is for this reason that the title of the present work refers to short horizontal pipes in which frictional effects are not dominant. The papers note that a hydraulic jump occurs in the water flow but does not suggest that flooding occurs when that jump is prevented by the air flow from entering the horizontal section.