EFFECT OF THE POSITION OF AN ORIFICE WITH RESPECT TO AN ELBOW IN CCF

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ABSTRACT

This paper presents experimental results on counter-current flow (CCF) and flooding in a test section containing a vertical and a horizontal run in which an orifice is placed. In particular, the influence of the position of various sized orifices with respect to the elbow between the vertical and horizontal runs is examined. The experimental technique used allowed not only the flooding limit to be determined, but also the entire partial liquid delivery region up to zero liquid penetration point to be determined as well. Experiments were also carried out for deflooding in order to study hysteresis effects. In general, it is observed that both the flooding limits and the delivered liquid flow rates decrease with decreasing the size of the orifice. It is also observed that the flooding limit seems to be independent of the position of the orifice. Furthermore, it is observed that when the orifice is closer to the elbow, the delivered liquid flow rate is lower for a given set of experimental conditions than when the orifice is far away from the elbow. Even though a hysteresis effect is present in the experiments, i.e., the deflooding point occurs when the superficial velocity is significantly lower than the gas superficial velocity at the flooding point, the deflooding points are seen to closely follow the partial delivery curve for all the cases studied.

1. INTRODUCTION

CCF in general and the Counter-Current Flooding Limit (CCFL) in particular are of great importance in the area of nuclear reactor safety analysis. In CANDU reactors, during some postulated loss of coolant accidents (LOCA), the water coming from the inlet and outlet headers enters the fuel channels through the feeder pipes. These feeders consist of vertical and horizontal runs. In some feeders devices are installed for flow adjustments and measurements. Following system depressurization, steam produced in the feeders and/or in the fuel channels may flow in a direction counter to that of the water, thereby creating vertical and horizontal counter-current two phase flows in the feeders. Under these conditions, the rate at which cooling water can enter the fuel channels may be limited by the flooding phenomena. During flooding, the liquid is partly entrained in the same direction as the steam flow. The liquid delivery is greatly affected by the geometry of the feeders, shape and number of fittings, flow area restrictions and their position as well as the way the feeder is connected to the header and to the end-fitting. Thus, characterisation of the flooding phenomena can be used to improve the modelling of CCF in computer codes used for the safety analysis of nuclear reactors.

The objective of this work is to study CCF and flooding in a test section containing a vertical and a horizontal run in which an orifice is placed. Results for the entire range of CCF phenomena from the onset of flooding up to the zero liquid penetration are studied. In particular, the influence of the position of the orifice with respect to the elbow on the partial liquid delivery, flooding and on the zero liquid penetration point is examined. Data on the hysteresis effect and the deflooding point are also presented.

2. PREVIOUS WORK

Over the last 30 years a great deal of experimental and analytical work has been done on the determination of the flooding point in vertical counter-current two phase flows. The same cannot, however, be said for counter-current two phase flows occurring in an elbow between vertical and horizontal pipes where the amount of information available in the open literature is quite limited. Similarly, while the influence of an obstruction on the flooding point in vertical counter-current two phase flows has been studied by a number of different researchers the amount of information available on this subject under horizontal flow conditions is rather scarce. In addition to that, no experiments have been carried out to determinate the influence of the position of a flow area restriction with respect to an elbow on the flooding points and on the partial liquid delivery. Nevertheless, we will examine the information available regarding the influence of the obstructions on the flooding phenomena under both vertical and horizontal CCF conditions as well as that available on the influence of an elbow between vertical and horizontal pipes.

2.1 Vertical Flow

Celata *et al.* [1] studied the influence of orifices on the delivered liquid flow rate under CCF conditions. They carried out experiments in a 20 *mm* internal diameter (I.D.) test section without obstructions with orifices having β ratios ($= D_{orifice} / D_{tube}$) of 0.60, 0.70, 0.75, 0.80, 0.85, 0.90, and 0.95. For a given orifice they observed that the delivered liquid flow rate was only a function of the gas flow rate and did not depend on the inlet liquid flow rate. They also found that for a given gas flow rate the delivered liquid flow rate decreased with decreasing orifice size. They also concluded that for a given β ratio, the zero liquid penetration point, the point where the delivered liquid flow rate is zero, was the same for all the liquid flow rates used in the experiments.

Tye *et al.* [2] and Davidson [3] carried out experiments for the determination of the flooding point in a 19 *mm* I.D. test section without an obstruction and with orifices having β ratios of 0.66, 0.72, 0.83, and 0.90. They found that the presence of the orifice significantly reduced the gas flow rate required to initiate flooding for a given liquid flow rate. Further, they found that this influence became more pronounced for smaller β ratios. Tye *et al.* [4] also carried out similar experiments in a 63.5 *mm* I.D. vertical test section for the characterisation of the entire partial delivery region of CCF from the point of onset of entrainment (flooding limit) up to the zero liquid penetration point. It was again found that the presence of the orifice significantly reduced the gas flow rate required to initiate flooding for a given liquid flow rate. Further, they observed that for each of the orifices studied, the delivered liquid flow rate was only a function of the gas flow rate.

and was independent of the inlet liquid flow rate. They also found that for a given orifice β ratio, the gas flow rate at the zero liquid penetration point was independent of the inlet flow rate.

2.2 Counter-Current Flow in Vertical or Inclined to Horizontal Pipes

Krowlewski [5] carried out CCFL experiments using vertical to horizontal and inclined to horizontal pipes. The test facility consisted of a 51 *mm* I.D., 584 *mm* long horizontal pipe connected to a vertical or inclined pipe by either a 90° or a 45° elbow. Air and water at atmospheric conditions were used as the working fluids. The point of onset of flooding was determined to be the point at which a sudden increase in the pressure drop across the test section occurred. Data were reported for a number of different geometrical configurations. For that most closely resembling the test facility used in the present study, the author's results indicate that there is a significant decrease in the gas flow rate required to provoke flooding as compared to that which would be required for the same tube diameter under vertical flow conditions.

Siddiqui *et al.* [6] carried out flooding experiments in a vertical to horizontal 90° elbow for various pipe diameters, pipe lengths and radius of curvature of the elbow. The authors found that at high liquid flow rates a hydraulic jump formed in the horizontal run close to the bend and that flooding was caused by slugging which occurred at this point. At low liquid flow rates, for the range of the tube diameters used, it was found that the hydraulic jump was very small and difficult to observe. The authors also observed that the flooding limit was dependent on the tube diameter, its length, as well as on the radius of curvature of the bend. The results indicate that for all the liquid flow rates studied the gas flow rates at the flooding point were much smaller than those corresponding to flooding in an equivalent vertical pipe. The authors also found that for the range of tube diameters studied, the square root of the non-dimensional superficial gas velocity at the zero liquid penetration point was constant.

Wan [7] studied the CCF of steam and water in an upright 90° elbow. Qualitatively the results were quite similar to those of Siddiqui *et al.* [6]. The author, however, identified three distinct flow patterns that characterised the experiments. These patterns were: *i*) steady CCF without slugging, *ii*) slugging with liquid carryover, and *iii*) slugging with an oscillating water column in the vertical run without liquid carryover.

Kawaji *et al.* [8] studied the CCFL in vertical and vertical to horizontal and downwardly inclined 51 *mm* I.D. pipes. For the horizontal pipes the experiments were carried out using two different lengths for the horizontal pipe: 2.54 *m* and 0.1 *m*. For the longest horizontal pipe and for low liquid flow rates the authors observed the formation of a hydraulic jump in the horizontal pipe just downstream of the elbow. Under these conditions, it was observed that flooding was triggered by slugging at the crest of the hydraulic jump. Furthermore, for the same inlet liquid flow rate flooding took place at lower gas velocities than those required for a vertical run only. At higher liquid flow rates the flooding mechanism changed and it was observed to occur due to slugging near the exit of the horizontal run.

Kawaji *et al.* [9] carried out experiments to determine the flooding limit in a 51 *mm* I.D. test section with multiple elbows and orifices having β ratios of 0.550, 0.670 and 0.865. Three different geometrical configurations were studied: double-vertical elbow in which the second and third elbow are in the vertical plane, double-horizontal elbow in which the second and third elbow are in the horizontal plane, and double-inclined elbow in which the second and third elbow are at 45° to the vertical plane. Although there are some differences in the results for the three different geometries studied, some qualitative observations can be made with respect to the effect caused by of the orifice size on the flooding point. The authors found that the orifice having the largest β ratio had very little effect on the flooding point as compared to the results of the experiments carried out without the orifice. For the two smaller orifices it was found that, for a given liquid flow rate, the flooding gas velocities were much smaller than those observed with the largest orifice and without the orifice cases. Further, the flooding gas velocity was found to decrease with decreasing the orifice β ratio.

Noel *et al.* [10] carried out both flooding and de-flooding experiments in a complex test section containing multiple vertical and horizontal or near horizontal runs without orifices. Similar to the observations made for vertical flows, their results have shown a significant difference in the gas flow rates at the flooding and deflooding points for all of the liquid flow rates studied.

Tye *et al.* [4] presented preliminary results of partial delivery experiments carried out in a 63.5 *mm* I.D. vertical to horizontal runs without an orifice and with various sized orifices placed at the middle of the horizontal run. They found that for a given inlet liquid flow rate and for a constant counter-current gas flow rate, the delivered liquid flow rate decreased with decreasing the orifice β ratio. They also found that the gas flow rate at the zero liquid penetration point corresponded to a unique value for each of the orifices used as well as for the case without orifice, and did not depend on the inlet liquid flow rate.

3. TEST FACILITY AND INSTRUMENTATION

The CCF test facility shown in Figure 1 can accommodate vertical test sections as well as test sections containing both vertical and horizontal runs. Water and air at close to atmospheric conditions are used as the working fluids. The water is supplied to the test section by a pump connected to a constant head water tank. The temperature of the inlet water is held constant at $20 \pm 0.5°C$. The air is supplied by the mains of the laboratory.

3.1 CCF Test Section Containing Vertical and Horizontal Runs

Figure 2 shows a schematic diagram of the test section containing both vertical and horizontal runs. The test section is constructed of 63.5 *mm* I.D. transparent Plexiglas tubes to allow flow visualisation. Both runs are supported by aluminium I-beams and adjustable brackets. The angle of the test section from the horizontal can be varied as required. For the experiments presented in this paper an angle of 90° between the vertical and the horizontal run was used. The major components of the test facility are:

1. the upper plenum which serves as a collector/seperator system for any liquid hold up during CCF and CCFL experiments,

2. the porous wall liquid injector which consists of a 63.5 *mm* I.D. tube with 800, 1 *mm* holes in the wall,
3. the test section that consists of a 2022 *mm* long vertical run and a 3327 *mm* long horizontal run. Both the vertical and horizontal runs contain flanges in which an orifice can be placed. The vertical and horizontal runs are connected by a 90° PVC elbow; they are centred in the elbow by two Plexiglas collars and are sealed using O-rings, and
4. the lower plenum which contains the liquid outlet including a water level control system and the air inlet system. The level control system is capable of maintaining the water level in the lower plenum constant (±1 *cm*) throughout the entire range of liquid flow rates, i.e., from full liquid delivery up to the zero liquid penetration point.

The flow area restrictions (orifices) are installed in the test sections by means of the flanges designed for this purpose. The positions of these flanges with respect to the elbow are shown in Figure 2. For the present work, the orifices were placed in the horizontal run only. The orifices are made of 1.5 *mm* thick stainless steel plates without a chamfered edge. The β ratios of the orifices used are 0.90, 0.83, 0.77, 0.72, 0.66 and 0.55; only the results obtained with orifices having β ratios of 0.83, 0.77 and 0.66 are presented in the paper.

3.2 Instrumentation

The test facility is instrumented to measure liquid and gas flow rates, inlet flow temperatures, and absolute pressures.

Liquid Flow Rate: The liquid flow rate is measured using "Flow Technology" turbine flow meters which cover the range from 0.05 to 4.54 m^3/h with an accuracy of better than 1% of full scale.

Gas Flow Rate: The gas flow rate is measured using a set of five "Brooks" rotameters covering the range from 0.085 to 132.5 m^3/h at an inlet pressure of 2 *bar*. The accuracy of the rotameters is 2% of full scale.

Absolute Pressure: The absolute pressure in the lower plenum is measured using a "Sensotec" pressure transducer; the range of the absolute pressure covered is from 0 to 0.14 *bar* with an accuracy of 0.25% of full scale.

Temperature: The temperature of the gas is measured with a thermocouple installed in the air inlet line with an accuracy of $\pm 0.5°C$. The temperature of the liquid is measured by using a RTD with an accuracy of $\pm 0.5°C$.

4. EXPERIMENTAL PROCEDURES

In the past, several different physical phenomena have been used to characterise the flooding point. For this reason, we will clearly state the definition of flooding as well as the experimental criterion used to determine the flooding point in this work (Bankoff & Lee [11]): *"for a given downward liquid flow the maximum upward gas flow rate for which full liquid delivery out the bottom of the tube is maintained, corresponds to the counter-current flooding limit."* It is important to note that the CCFL is just a limit for the gas flow rate beyond which only partial liquid delivery out of the lower end of the test section will occur. This point corresponds to the maximum gas flow rate for which full liquid delivery still exists, and it is the most widely accepted experimental criterion for the point of flooding (Bankoff & Lee [11], and Dukler *et al.* [12]). Having defined our criterion for the detection of the flooding point we will now describe the experimental procedure.

The first point that could be studied for each liquid flow rate was determined by fixing the required inlet liquid flow rate and then, slowly increasing the gas flow until a point where a measurable amount of liquid entrainment was observed. The subsequent experiments beyond this initial point were carried out by fixing the liquid and gas flow rates and collecting and weighing the entrained liquid using the collection system located in the upper plenum. In this manner the entire range of CCF phenomena from the point of inception of entrainment to the zero liquid penetration was studied for a complete range of inlet liquid flow rates. In order to minimise the scattering in the data, on average 20 *kg* of entrained liquid (water) was collected for each run. For the experiments presented in this paper, the range of inlet liquid flow rates covered is from 0.1 m^3/h to 2.5 m^3/h.

In order to study the hysteresis effect, the following procedure was used: for a given inlet liquid flow rate, the gas flow was fixed just beyond the value corresponding to the flooding limit. The gas flow rate was then, slowly decreased until full liquid delivery (total deflooding) was re-established. In order to follow the evolution of the locus of partial liquid delivery between the flooding limit and the point where deflooding occurs, for each inlet liquid flow rate and within the corresponding range of gas flow rates, a number of partial liquid delivery points were determined.

5. EXPERIMENTAL RESULTS

Even though, as has been mentioned above, the experiments were carried out using a wide range of orifice β ratios, only the experimental results obtained with orifice having β ratios of 0.83, 0.77 and 0.66 are included in the paper. The results for the partial liquid delivery, the flooding, and the hysteresis effect are presented separately.

5. 1 Partial Liquid Delivery

The results on partial liquid delivery are shown in Figures 3a-c. In order to simplify the presentation for the cases of orifices having β ratios of 0.77 and 0.66 only the best fit to the data points are given in the figures. Figure 3a. shows the data obtained for the orifice having a β ratio of 0.83; it can be seen that for both orifice positions the delivered liquid superficial velocities decrease smoothly with increasing gas superficial velocity. When the orifice is located at position 1 (closer to the elbow), for the largest inlet liquid superficial velocities and for gas superficial velocities between 0.7 and 1.5 *m/s*, a plateau region in the delivered liquid superficial velocity developed. For the same range of inlet gas superficial velocities and for the case when the orifice is located at position 2 (see Figure 2), the formation of a plateau region in the delivered superficial liquid velocity is much less apparent. For gas superficial velocities lower than 2 *m/s* the liquid superficial velocities are substantially higher when the orifice is located further away from the elbow. For gas superficial velocities higher than 2 *m/s* the position of the orifice does not affect the delivery liquid flow rate. Furthermore, for both orifice positions the zero liquid penetration point seems to be independent of the orifice location.

Figures 3b and c show the best fit of the delivered liquid superficial velocities vs. the gas superficial velocities for both orifice positions, for the orifices having β ratios of 0.77 and 0.66 respectively. In the first case, β=0.77, for both orifice positions and for gas superficial velocities between 0.75 and 1.8 *m/s* a plateau region is observed. Similarly to that observed in previous case (β=0.83), for gas superficial velocities lower than 2 *m/s* the delivered liquid superficial velocities are higher when the orifice is located at position 2 (far away from the elbow, see Figure 2). For gas superficial velocities higher than 2 *m/s* the position of the orifice does not affect the observed liquid delivered flow rates. Similarly to the case of β=0.83, the zero liquid penetration point seems to be independent of the position of the orifice with respect to the elbow. For the orifice having a β ratio of 0.77, Figure 3c, the location of the orifice with respect to the elbow does not affect the delivered liquid. For gas superficial velocities between 1.5 and 0.7 *m/s* and for both orifice locations a plateau region is observed. Once again, the zero liquid penetration point seems to be independent of the position of the orifice with respect to the elbow.

Comparing Figures 3a, b and c, it can be seen that in general for the highest inlet liquid superficial velocities and for gas superficial velocities lower than 2 *m/s* the delivered liquid superficial velocity is lower for the case where the orifice is located at position 1 than for the case when it is located at position 2. This difference decreases with decreasing the orifice β ratio. The range of experimental conditions over which the difference in the delivered liquid flow rates is more pronounced corresponds to the plateau region. It can also be seen that for low gas superficial velocities the delivered liquid superficial velocity drops quite rapidly for both orifice position. This rapid drop is, however, more important when the orifice is closer to the elbow (position 1). For gas superficial velocities higher than 2 *m/s* the partial liquid delivery results are almost identical for both orifice positions. Furthermore, for all the orifices tested the point which corresponds to the zero liquid penetration seems to be only a function of the orifice β ratio and does not depend on the orifice position with respect to the elbow.

For all the cases studied, it has been observed that for a given gas superficial velocity and inlet liquid superficial velocity, the delivered liquid superficial velocity decreases with decreasing orifice β ratio. Visual observations have shown that the disturbance that lead to partial liquid delivery always formed in the elbow. A pulsating column was formed in the vertical run which caused large amplitude waves to form in the horizontal run. These waves were reflected by the orifice and travelled back towards the elbow; it was then possible for a given reflected wave to interfere constructively with those waves generated by the pulsating column above the elbow. If the height of the wave resulting from the meeting of the two waves was sufficient to bridge the tube, a liquid slug resulted which was then blown violently back into the elbow and into the vertical run. While the mechanisms which govern the partial liquid delivery are similar regardless of whether the orifice is located at position 1 or at position 2, significant qualitative differences have nevertheless been observed. When the orifice is located at position 1, the liquid carryover is caused by the formation of small high frequency highly aerated slugs in the horizontal run which travel at a very high velocity. However, the liquid carryover, when the orifice is located at position 2, is seen to be due to very large low frequency liquid rich slugs which appear to move at a much lower velocity than those observed when the orifice is located at position 1. The observed differences in slug frequencies and velocities can be explained by the following: each oscillation of the pulsating column in the vertical run causes a wave in the horizontal run which travels towards the orifice. This wave is partially reflected by the orifice and returns towards the elbow. When a wave travelling towards the orifice meets a reflected wave, a bridge can be formed in the tube creating a liquid slug which is driven back towards the elbow by the counter-current gas flow. If the distance between the orifice and the elbow is large, the length of the resulting liquid slug will be greater due to the amount of liquid collected by the slug between its point of formation and the elbow (orifice position 2). Conversely, if the orifice is close to the elbow, the slug length will be smaller. If the orifice is far from the elbow, the amplitude of the waves caused by the pulsating column will gradually decrease as they travel towards the orifice. If these waves have a lower amplitude, the reflected waves will also have a lower amplitude. Thus, the probability that the resulting wave bridges the tube decreases with the distance between the elbow and the orifice. This phenomena of amplitude decrease can partially explain the lower wave frequency when the orifice is at position 2. A complex combination of these two phenomena (slug frequency and slug length) influence the partial delivery results when an orifice is installed in the horizontal run. Typical slugs formed in the horizontal run resulting from the meeting of an incident and a reflected wave for the cases where the orifice is located at position 1 and at position 2 are shown in Figures 3d and 3e respectively. Comparing these two pictures it is clear that the resulting slug is much larger when the orifice is located at position 2.

5.2 Flooding Results

The flooding results are presented in Figures 4a and b. It is important to point out that Figures 3a-c represent the locus of partial delivery and **not** the flooding limits. The relationship between the partial liquid delivery and the flooding limit is illustrated for an orifice having β=0.77 in Figure 4a. In examining this figure it is important to recall that the flooding limit corresponds to the maximum gas superficial velocity for which full liquid delivery still exists. From the insert in the figure it can be seen that as the superficial velocity of the gas is increased the delivered liquid superficial velocity remains constant at its inlet value until a particular gas superficial velocity is reached; at this point the delivered liquid superficial velocity drops suddenly. The maximum gas superficial velocity for which the delivered liquid superficial velocity retains its inlet value corresponds to the flooding limit. The insert in Figure 4a shows the flooding limit as well as the partial delivery results for one particular inlet liquid superficial velocity (0.1315 *m/s*). It can be seen that for this orifice the locus of flooding points lies considerably above the locus of partial delivery points for most of the range of gas superficial velocities covered. The two curves approach each other at the extremes of very low and very high inlet liquid superficial velocities. Figure 4b shows the flooding limit for both orifice positions and for all of the orifice sizes that have been included in the paper. It can be seen from this figure that the position of the orifice with respect to the elbow between the vertical and the horizontal run has almost no influence on the flooding point. This is most likely due to the fact that the mechanism that leads to flooding always occurs at the elbow. The influence of the orifice in this case is only to increase the water level at the elbow. It is clear from Figure 4b that for a given inlet liquid superficial velocity the gas superficial velocity at the flooding point decreases with decreasing orifice β ratio. Furthermore, the position of the orifice seems to have no influence on the mechanism by which flooding occurs. In general it has also been observed (compare the results given in Figures 3a-c with those of Figure 4b) that the relative drop between the locus of flooding points and the locus of partial liquid delivery increases with decreasing β ratio.

5.3 Hysteresis Effect

Figures 5a and b show the deflooding points for the cases where orifices having β ratios of 0.83 and 0.77 were located at positions 1 and 2 respectively (See Figure 2). The best fit curves for the partial delivery experiments and for the flooding points are also presented on the same figures. It can be seen that for the aforementioned orifice sizes and for both orifice positions, the deflooding points follow almost exactly the curves of the partial delivery results. Similar results were also obtained with other orifice β ratios (Tye *et al.* [13]). This indicates that in the post flooding state these curves define a unique relationship between the delivered liquid superficial velocity and the gas superficial velocity which do not depend on whether the gas flow is increasing or decreasing. For each inlet liquid superficial velocity, a small difference between the deflooding results and the partial delivery curves may be seen for the highest delivered liquid superficial velocities. These last points which correspond to the lowest gas superficial velocities are the deflooding points for each particular liquid inlet superficial velocity. It can be observed that after flooding has been initiated, it is necessary to substantially reduce the gas flow rate to re-establish full liquid delivery (deflooding point). For all the cases studied the differences found between gas superficial velocity corresponding to the flooding point and the gas superficial velocity corresponding to deflooding point indicate that there is a significant hysteresis effect. It can also be seen that, as was observed in the liquid delivery experiments, for the orifices having β ratios of 0.83 and 0.77 the delivered liquid flow rate is higher when the orifice is located at position 2 than when it is located at position 1. Furthermore, as in the partial delivery experiments, and for the cases of orifices having β ratios of 0.66 or lower (not presented in the paper) the delivered liquid flow rates with decreasing gas flow rates are almost identical for both orifice positions (Tye *et al.* [13]).

6. CONCLUSIONS

Experiments were carried out to study the entire range of CCF from the point of onset of entrainment up to the zero liquid penetration point in a test section containing a vertical and a horizontal run with an orifice installed in the horizontal run. It was observed that the liquid delivery flow rates are substantially affected by both the orifice β ratios and the orifice position with respect to the elbow. For a given gas superficial velocity, and for orifices having β ratios of 0.77 or greater, the partial liquid delivery is much higher when the orifice is located further away from the elbow. A phenomenological explanation for this behaviour, based on the amplitude and frequency of the waves travelling in the horizontal run has been presented. The influence of the position of the orifice with respect to the elbow on partial liquid delivery start disappearing for orifices having β ratios of 0.66 or lower. In all the cases studied the zero liquid penetration point appeared to be only function of the orifice size.

Flooding results show that the position of the orifice with respect to the elbow does not affect the flooding point. This is quite possibly due to the fact that flooding is controlled by the elbow and not by the position of the orifice. Further, it was observed that flooding always occurs as a fast transition between the points of full and partial liquid delivery, and that for a given inlet liquid flow rate the gas flow rate required to produce flooding decreases with decreasing the orifice β ratio.

In general, deflooding experiments have shown that after reaching the flooding point, it is necessary to substantially decrease the gas superficial velocity before the deflooding condition is reached. Further, it was observed that the locus formed by the deflooding points closely follow the locus of the partial liquid delivery points. Thus, deflooding is affected by the position of the orifice with respect to the elbow in a manner similar to the partial liquid delivery.

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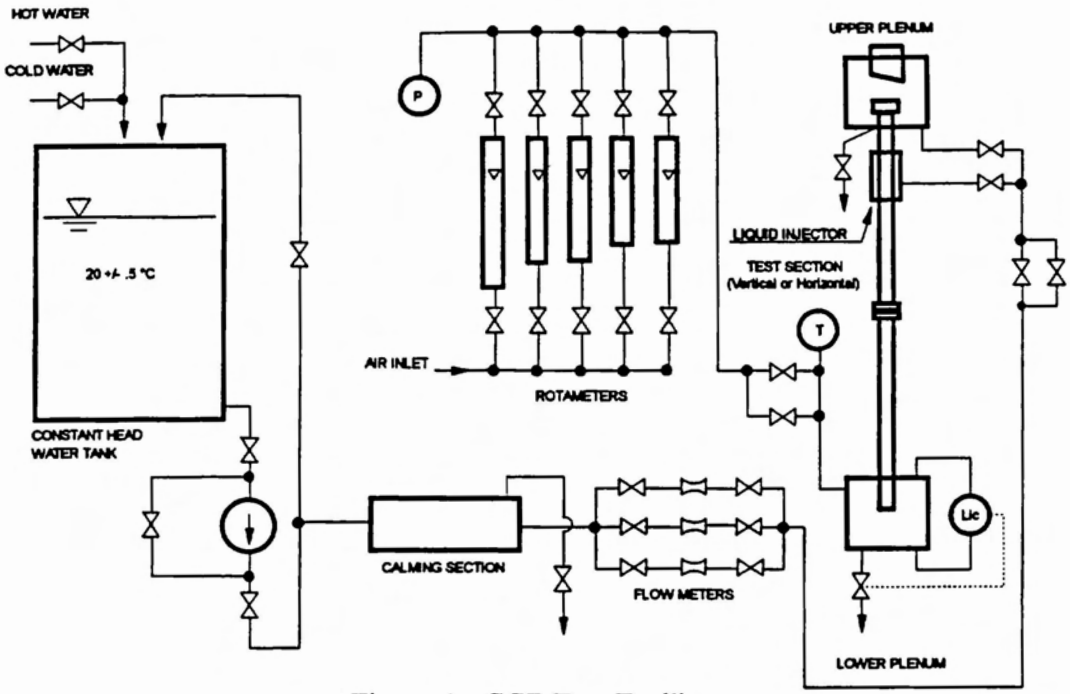

Figure 1. CCF Test Facility.

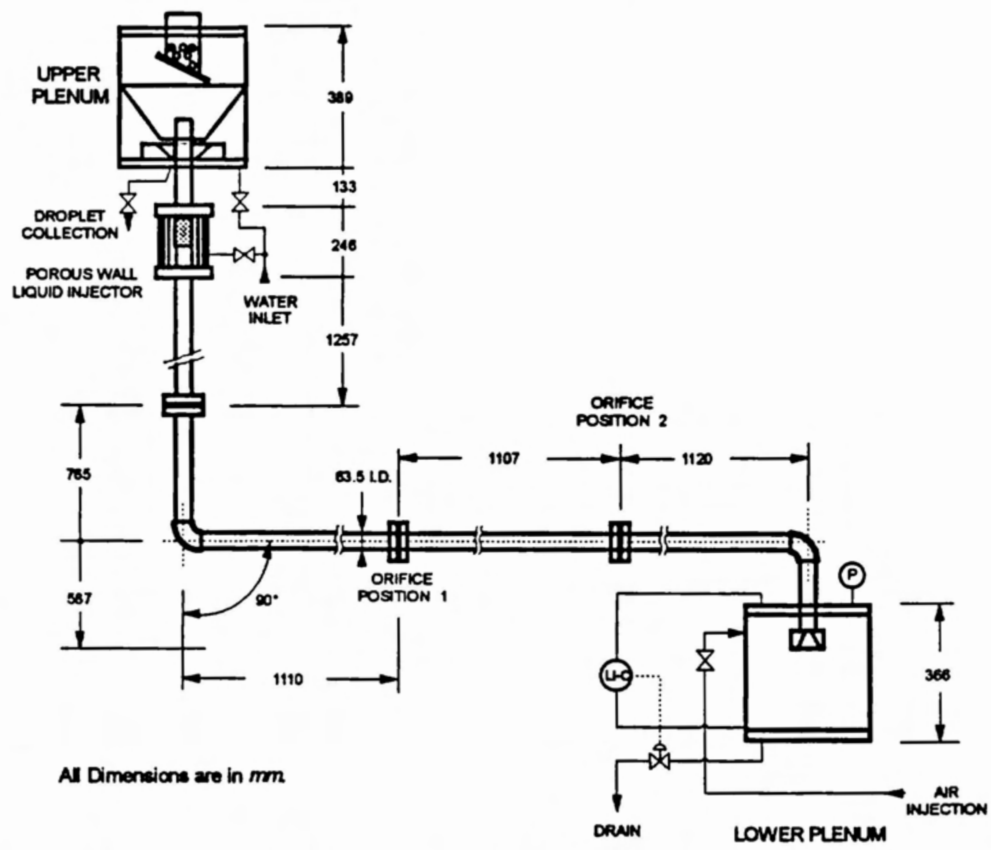

Figure 2. Test Section with Vertical and Horizontal Runs with Two Orifice Positions.

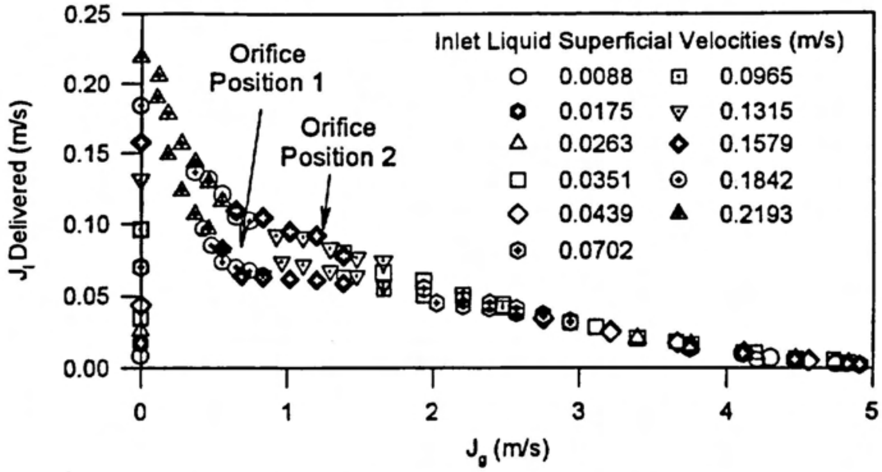

Figure 3a. J_l Delivered vs J_g (β=0.83, Orifice Position 1 & 2).

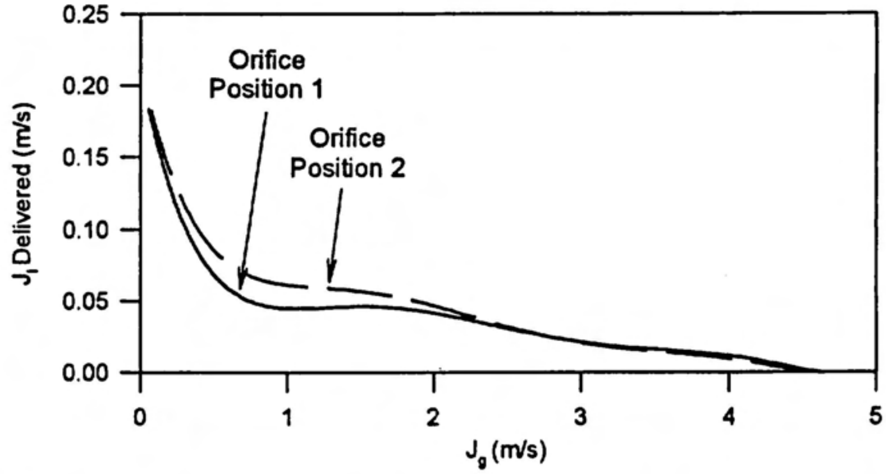

Figure3b. Best Fit of J_l Delivered vs. J_g (Orifice β=0.77 at Positions 1 & 2).

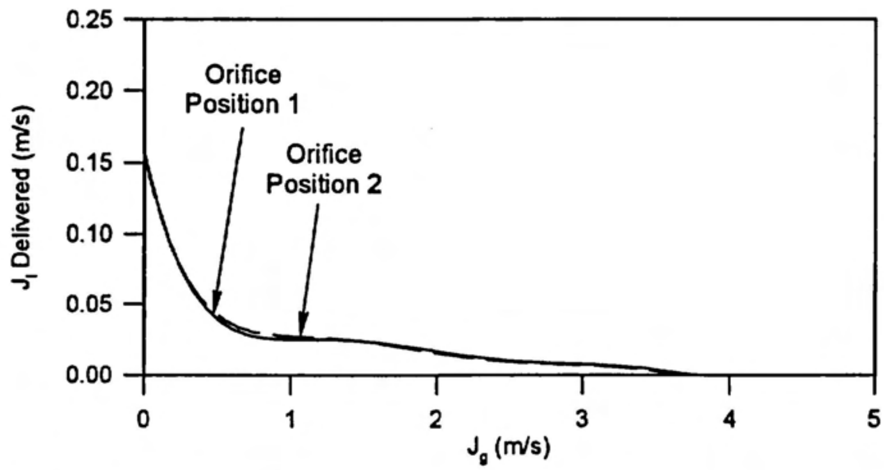

Figure3c. Best Fit of J_l Delivered vs. J_g (Orifice β=0.66 at Positions 1 & 2).

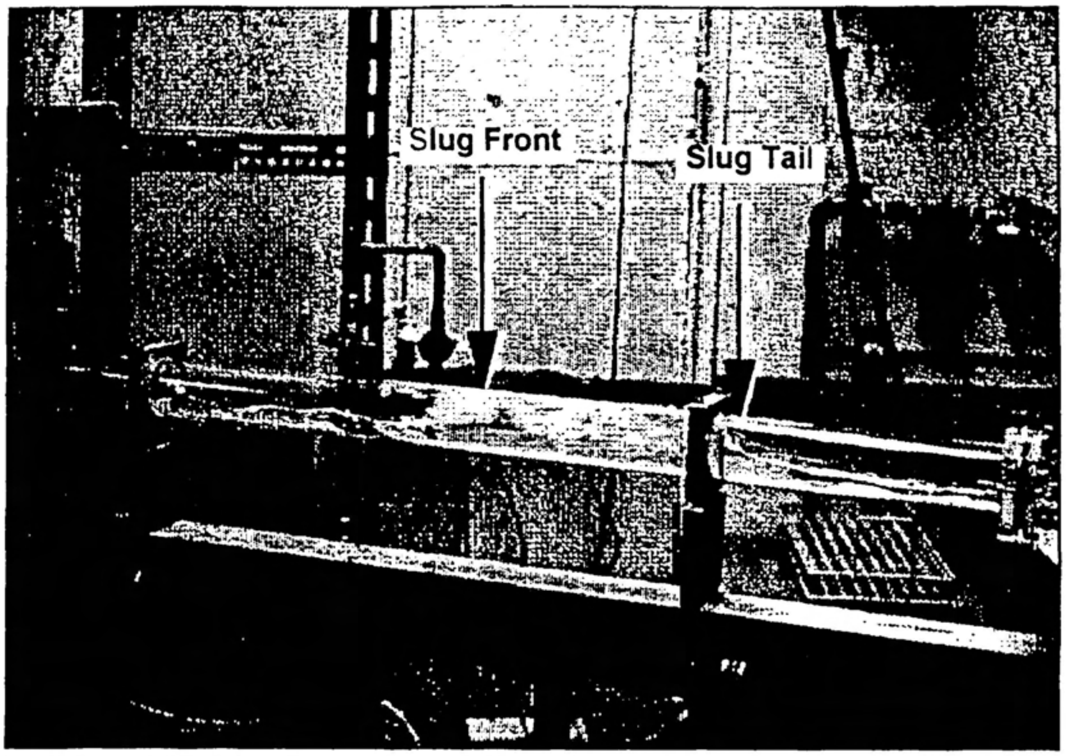

Figure 3d. Slug Produced When Orifice is at Position 1.

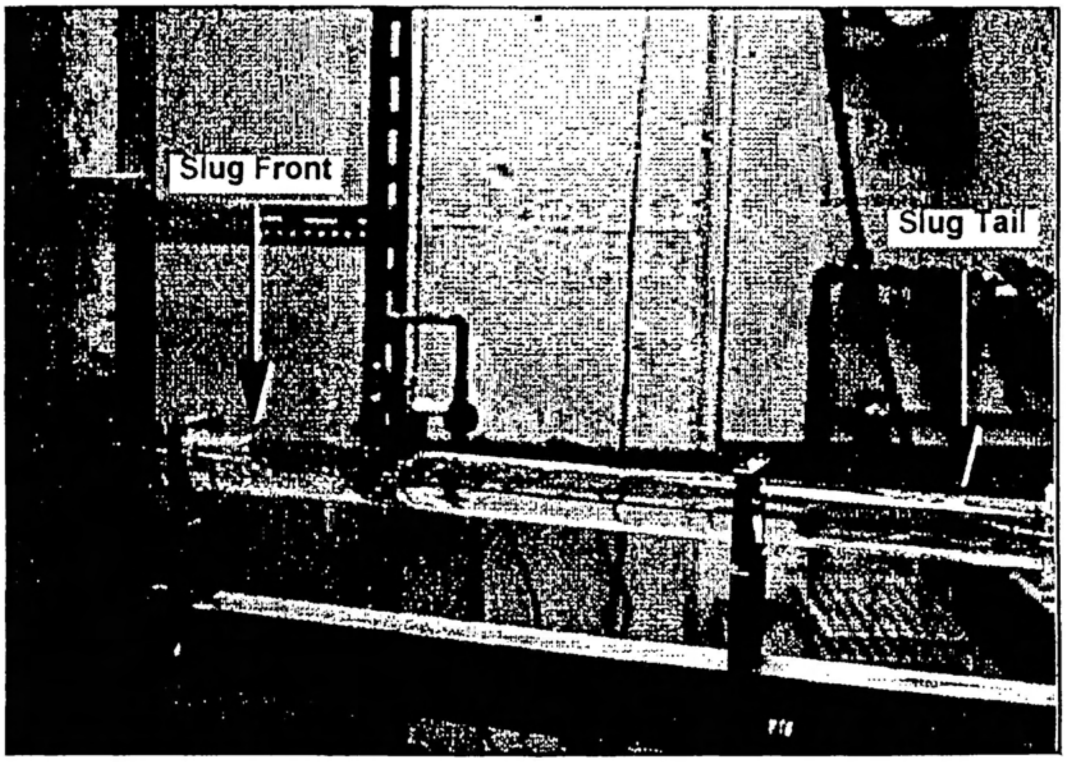

Figure 3e. Slug Produced When Orifice is at Position 2.

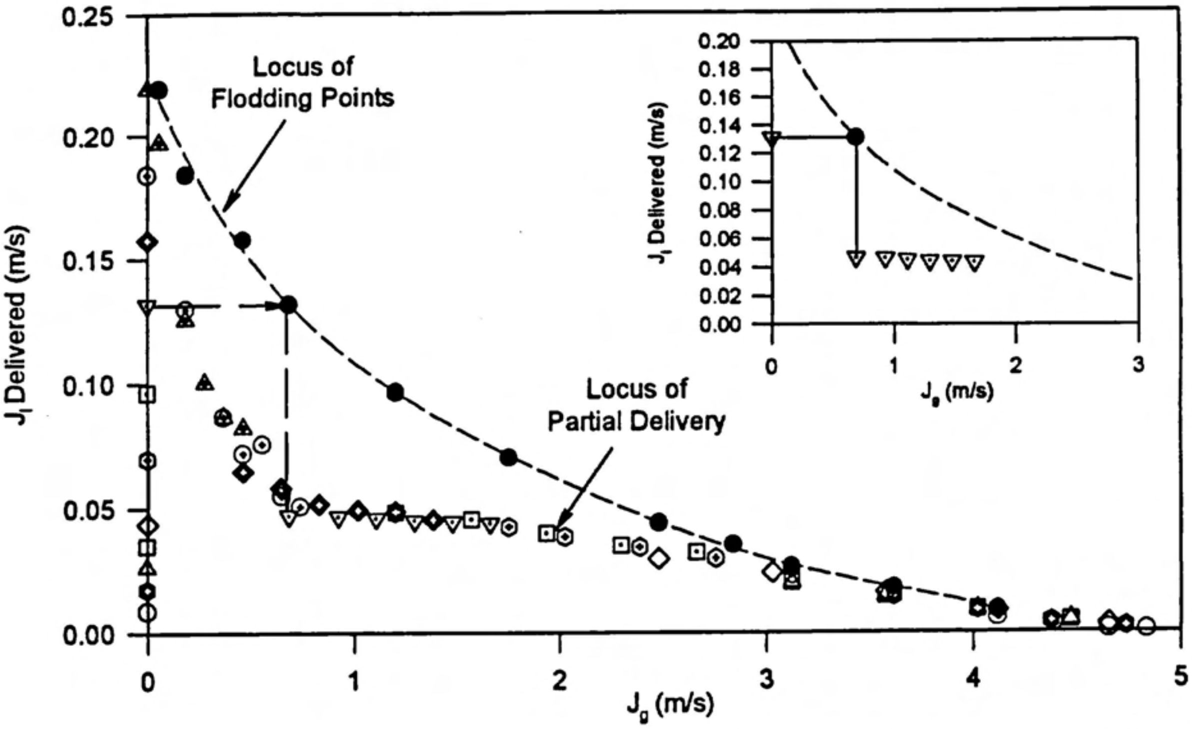

Figure 4a. J_l Delivered vs J_g and Flooding Points, Orifice β=0.77 Located at Position 1.

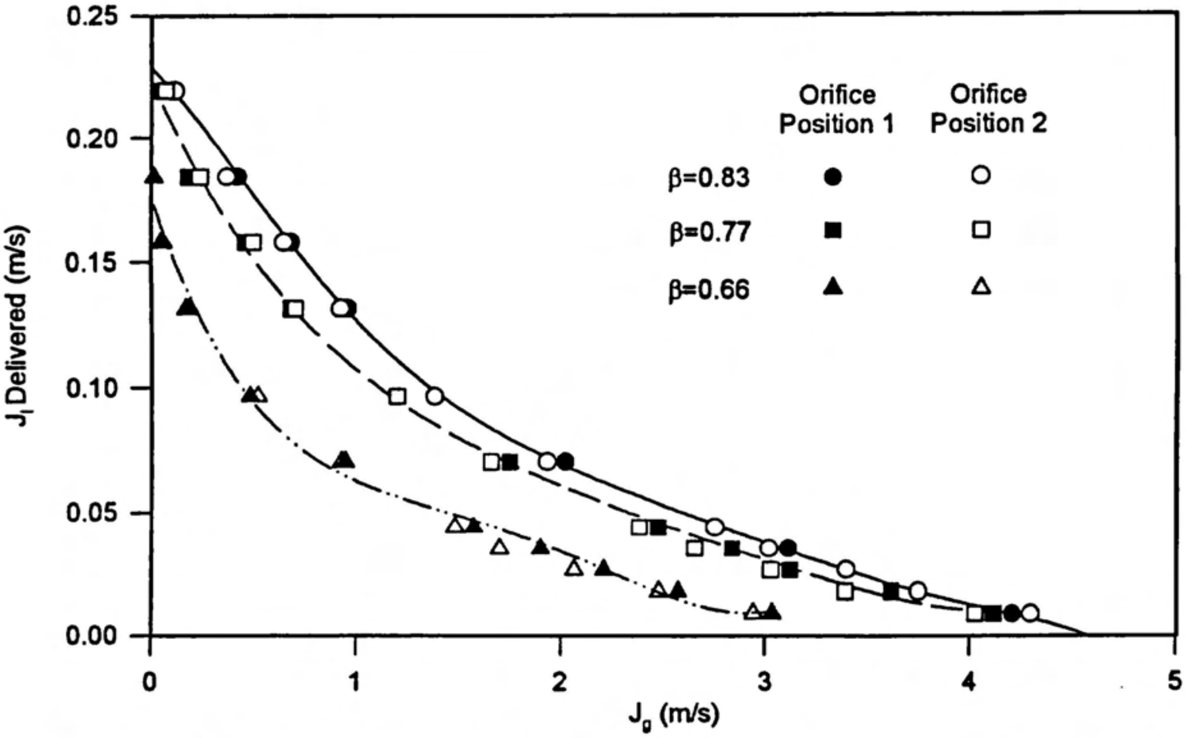

Figure 4b. Comparison of Flooding Points, Orifice Positions 1 & 2 (β=0.83, 0.77 and 0.66).

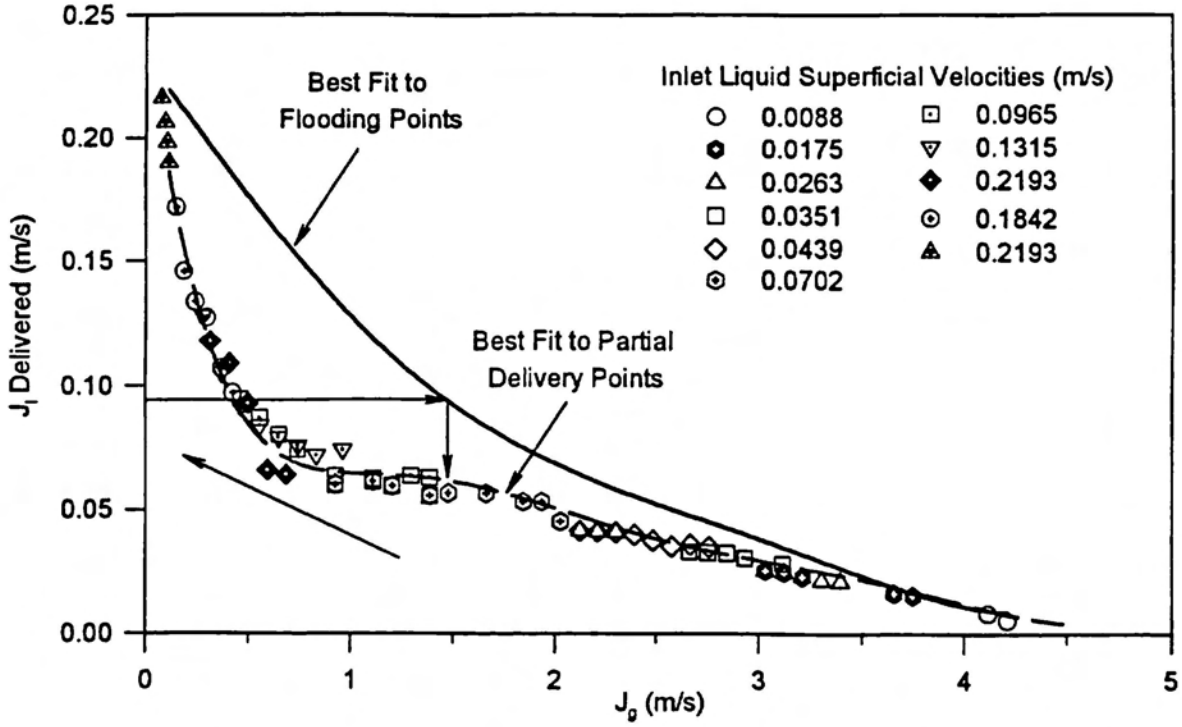

Figure 5a. Partial Delivery Results with Decreasing Gas Flow, Orifice β=0.83 at Position 1.

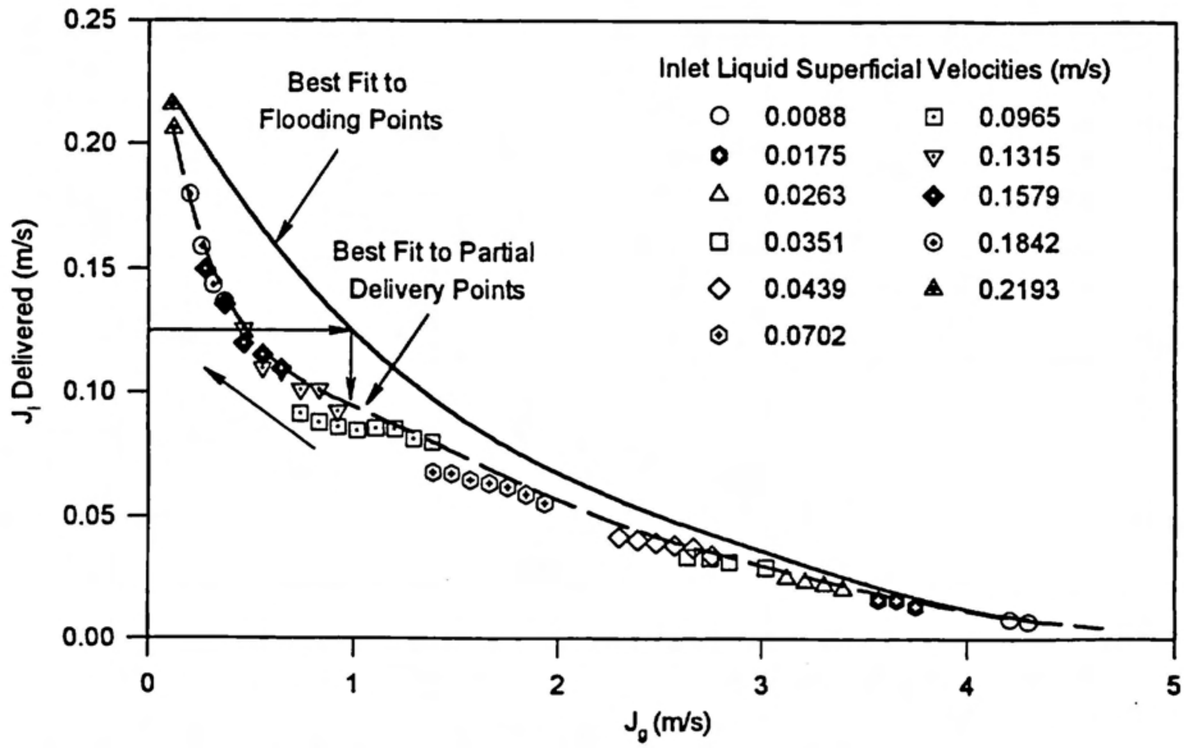

Figure 5b. Partial Delivery Results with Decreasing Gas Flow, Orifice β=0.83 at Position 2.

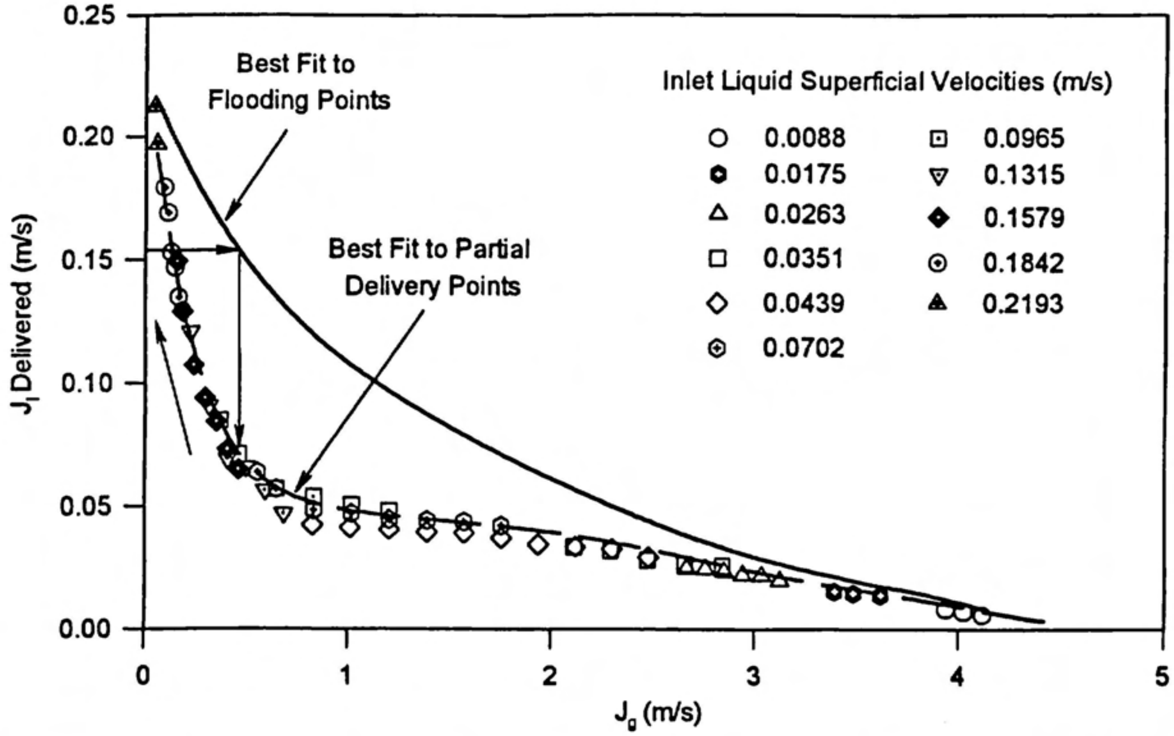

Figure 5c. Partial Delivery Results with Decreasing Gas Flow, Orifice β=0.77 at Position 1.

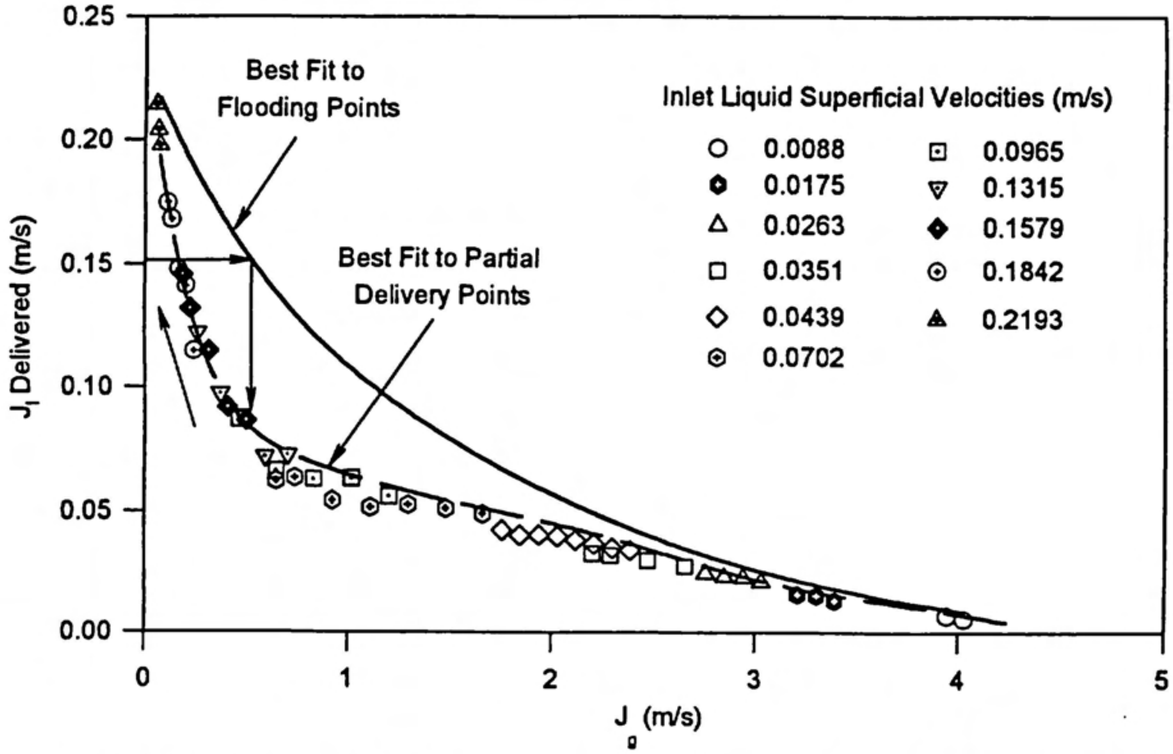

Figure 5d. Partial Delivery Results with Decreasing Gas Flow, Orifice β=0.77 at Position 2.