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PREDICTION OF THE FLOODING POINT IN A VERTICAL TO HORIZONTAL TUBE WITH AND WITHOUT OBSTRUCTIONS

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Abstract

This paper presents a model to predict the flooding point in a test section containing vertical and horizontal legs both with and without an orifice located in the horizontal leg. The predictions of the flooding point obtained using this model are compared to experimental results obtained both in our laboratory and those of other researchers. It will be shown that in general the agreement between the predicted and experimental flooding points is excellent. It should be pointed out that to the best of the authors knowledge there are no models available in the open literature which are capable of predicting the flooding point occuring in an elbow between a vertical and a horizontal leg in which an orifice is placed.

1. Introduction

Counter–Current Flow (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 a postulated loss of coolant accident (LOCA), the water coming from the inlet and outlet headers enters the fuel channels through the feeder pipes. These pipes consist of vertical and horizontal runs. In some feeders, orifices and/or venturi type flow obstructions are installed for flow adjustments and measurements. Steam produced in the feeders and/or in the fuel channels may flow in the direction opposite to that of the water, thereby creating vertical and horizontal counter–current two–phase flows in the feeder pipes. 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. Thus, knowledge of the flooding phenomena in a geometry similar to the header–feeder system in a CANDU reactor is of prime importance in the safety analysis of nuclear reactors in order to improve the prediction of the time required for the emergency cooling injection system to refill the fuel channels. The work presented in this paper focuses on the development of a model to predict the flooding point occuring in an elbow between a vertical and a horizontal leg in which an orifice is placed.

2. Previous Work

The number of studies which have been carried out on counter–current flows in inclined and vertical–to–horizontal flows is quite limited. Krowlewski [1980] carried out flooding experiments for vertical to horizontal and inclined to horizontal flows. The test facility consisted of a 51 *mm* I.D. 584 *mm* long horizontal leg connected to a vertical or inclined leg by either a 90° or a 45° elbow. Air and water at atmospheric conditions were used as the working fluids. Krowlewski's [1980] 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.* [1986] carried out experiments on air–water flows in a pipe consisting of a vertical leg connected to a horizontal leg by an elbow. They found that the gas velocities at flooding were well below those expected for vertical pipes, and were found to depend on tube diameter, the length of the lower leg and on the radius of curvature of the bend.

Ardron & Banerjee [1986] developed a model to predict the experimental results of Siddiqui *et al.* [1986] for flooding in vertical–to–horizontal pipes. The model was based of the prediction of the onset of slugging at the crest of the hydraulic jump that occurs in the horizontal leg downstream of the elbow. They also tested their model against the experimental results of Krowlewski [1980]. The predictions of this model were quite good for both sets of experimental results, however, this model is incapable of taking into account the influence of an orifice in the horizontal leg on the flooding point.

Wan & Krishnan [1986] performed experiments on air–water counter–current flows in vertical–to–horizontal and in vertical–to–slightly inclined pipes. Experimental data obtained for the vertical-to-horizontal pipes are in good agreement with the experimental data of Siddiqui *et al.* [1986] and with the predictions by Ardron & Banerjee [1986] for low liquid flow rates (${J_l^*}^{\frac{1}{2}} < 0.5$).

Kawaji *et al.* [1991] studied air–water counter–current flows in vertical–to–horizontal and in vertical–to–downwardly inclined pipes containing elbows of varying angle. For low liquid flow rates (${J_l^*}^{\frac{1}{2}} < 0.4$) in vertical–to–horizontal pipes they confirmed the qualitative observations and experimental results of Siddiqui *et al.* [1986] as well as the predictions obtained by Ardron & Banerjee [1986]. For higher liquid flow rates they found that the Ardron & Banerjee model [1986] fails to reproduce experimental data.

Kawaji *et al.* [1993] 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, qualitative observations can be made as to the effects 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 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 in the no orifice case. Further, the flooding gas velocity was found to decrease with decreasing orifice β ratio.

Tye *et al.* [1995] carried out experiments not only to determine the flooding point in an elbow between a vertical and a horizontal leg in which an orifice was placed but also to characterize the entire range of counter–current two–phase flow phenomena right up to the point of zero liquid delivery (i.e., complete carryover). It was found that for a given liquid flow rate the flooding point was much lower than that corresponding to vertical flow conditions. As in the case of Kawaji *et al.* [1993] they found that the flooding point also decreased with decreasing orifice β ratio. They also found that a significant increase in the gas flow rate beyond that corresponding to the flooding point was required to reach the point of complete liquid carryover.

3. Model for Horizontal CCFL

The guiding principle for the model development is [Wilcox 1994]: *"a really good model should introduce the minimum amount of complexity while capturing the essence of the relevant physics."* To this end visual observations of the behaviour of the counter–current flow just prior to and at the onset of flooding were heavily relied upon to guide the model development. It was observed that as the gas flow rate was increased, entrained droplets began to appear in the gas stream in the vertical leg just above the elbow. At gas flow rates below that corresponding to the flooding point the concentration of entrained droplets was quite small. This concentration increased quite rapidly as the flooding point was reached. It was thus postulated that the onset of flooding was in some way linked to the onset of entrainment.

Thus a mechanistic model based on the following premise has been developed for the prediction of the flooding point in an elbow between a vertical and a horizontal leg: *flooding occurs as a results of a buildup of the droplets entrained from the crest of the hydraulic jump which occurs inside the elbow.*

In order to calculate the height of the hydraulic jump it is necessary to first obtain the depth of the flow upstream of the jump. To do this, it is assumed that the void fraction in the supercritical (i.e., $Fr > 1$) region in the horizontal leg is equal to that in the vertical leg. This is a reasonable assumption as it has been observed that the hydraulic jump takes place right at the start of the horizontal leg. It is now necessary to find a means of calculating the film thickness and liquid velocity in the vertical leg. Since the flooding point in a test section containing both a vertical and a horizontal run is well below that occuring in vertical flow only, and further, since it has been shown experimentally [Zabaras 1985] that for vertical flow below the flooding point, the measured film thickness under counter–current flow conditions is very close to the Nusselt film thickness it is reasonable to assume, for calculation purposes, that the film thickness is equal to the Nusselt film thickness as given by:

$$\delta = \left(\frac{3\mu_l \dot{m}_l}{g\rho_l^2 \pi D} \right)^{1/3} \quad . \tag{1}$$

The void fraction is then obtained from:

$$\alpha = \left(1 - \frac{2\delta}{D} \right)^2 \quad . \tag{2}$$

It is assumed that the void fraction in the horizontal leg before the hydraulic jump is equal to that in the vertical leg. Thus, the film thickness in the horizontal leg, δ_h, can be obtained by the iterative solution of:

$$\alpha = 1 - \frac{1}{\pi} * \arccos(\frac{D - 2\delta_h}{D}) - \left(\frac{D/2 - \delta_h}{\pi D^2/4} * \sqrt{\delta_h * (D - \delta_h)} \right) \quad , \tag{3}$$

The upstream critical depth of the flow and the height of the hydraulic jump can be obtained using Straub's method [French 1985]:

$$\delta_c = \left(\frac{1.01}{D^{0.264}}\right) * \left(\frac{Q_l}{\sqrt{g}}\right)^{0.506} \quad , \tag{4}$$

where Q_l is the volumetric flow rate of the liquid phase and δ_c is the critical depth. The height of the hydraulic jump may then be obtained by:

$$\delta_j = \begin{cases} \left(\delta_c^2/\delta_h\right) & \text{for } Fr < 1.7 \\ \left(\delta_c^{1.8}/\delta_h^{0.73}\right) & \text{for } Fr \geq 1.7 \end{cases} \quad , \tag{5}$$

where Fr is the upstream Froude number which is defined as:

$$Fr = \frac{|v_l|}{\sqrt{g\delta_h}} \quad . \tag{6}$$

The void fraction at the crest of the hydraulic jump, α_j, is then calculated from:

$$\alpha_j = 1 - \frac{1}{\pi} * \arccos(\frac{D - 2\delta_j}{D}) - \left(\frac{D/2 - \delta_j}{\pi D^2/4} * \sqrt{\delta_j * (D - \delta_j)}\right) \quad , \tag{7}$$

and the corresponding liquid velocity is obtained from:

$$|v_l| = \frac{\dot{m}_l}{\rho_l \alpha_j \pi D^2/4} \tag{8}$$

where $\dot{m}_l$ is the liquid mass flow rate. **Note: the velocity is defined to be positive in the direction of the gas flow**. The Ishii & Grolmes [1975] criterion for the inception of entrainment is then applied at the crest of the hydraulic jump. This criterion is that the drag force, F_d, acting on the crest of a roll wave is greater than the retaining force of the surface tension, F_σ:

$$F_d \geq F_\sigma \quad , \tag{9}$$

The drag force on the wave crest is given by:

$$F_d = C_d \lambda a \frac{\rho_g v_r^2}{2} \quad , \tag{10}$$

where λ is the wave length, v_r is the relative velocity between the gas and the liquid phases given by $v_r = v_g - v_l$, a is the wave amplitude, and the drag coefficient is given by an analogy to the drag for deformed particles and is taken to be $C_d \approx 1$. The retaining force of the surface tension is given by:

$$F_\sigma = C_s \lambda \sigma \quad , \tag{11}$$

where C_s is an interfacial shape coefficient, Ishii & Grolmes [1975] specify this coefficient as being $C_s \leq 0.77$. The wave amplitude, a, is given by Ishii & Grolmes [1975] as:

$$a = \sqrt{2} C_w \frac{\mu_l}{\rho_l} \sqrt{\frac{\rho_l}{\tau_i}} \frac{1}{\sqrt{f_i}} \quad . \tag{12}$$

where C_w is a factor which is used to account for the effect of the surface tension on the internal flow, details regarding the calculation of C_w are given in Ishii & Grolmes [1975]. They propose that the friction factor, f_i, be calculated using the relationship given by Hughmark [1973] and τ_i is the interfacial shear stress. In order to apply this model for the prediction of the flooding point in a test section containing vertical and horizontal legs the following procedure used is:

1. For a given experimental liquid flow rate the Nusselt film thickness is calculated using equation (1), the corresponding void fraction is then obtained using equation (2),
2. The film thickness of the stratified flow before the hydraulic jump, δ_h, is then obtained by an iterative solution of equation (3) using the void fraction obtained in the previous step,
3. Equations (4) and (5) are then used to calculate the critical depth of the flow and the height of the hydraulic jump. The void fraction at the crest of the hydraulic jump is then obtained using equation (7) and the corresponding liquid velocity is obtained from equation (8).
4. The criterion for the inception of entrainment given by equation (9) is then calculated using a guessed gas velocity where the wave amplitude is calculated using equation (12). The gas velocity is updated until the inequality which defines the point of inception of entrainment is satisfied.

For the specific case when an orifice is placed in the horizontal leg a provision must be made to take into account its influence on the flooding point. It is assumed that the orifice creates a stagnation region in the flow. The height of this stagnation region is calculated to be the height of the liquid level in the horizontal leg produced by the presence of the orifice multiplied by $1/\beta$:

$$h_s = \frac{(1-\beta)}{\beta}\frac{D}{2} \quad .\psi \tag{13}$$

The height of the hydraulic jump calculated in step 3 is offset by the height of the stagnation region, h_s, and the rest of the calculation is carried out in the same manner as for the case without an orifice as described above.

4. Comparison of Predicted and Experimental Flooding Points

Details regarding the experimental facility, procedure and results obtained during the course of this research project are given in Tye *et al.* [1995]. The results of a comparison between this model and our experimental results for the case without an orifice are shown in Figure 1. A comparison of the predicted and experimental flooding points using our data and the Ardron & Banerjee [1986] flooding correlation is also presented. It can be seen that the present model is in slightly better agreement with the experimental results than that of Ardron & Banerjee [1986].

Comparisons of the predictions of the present CCFL model against some of the results of Krowlewski [1980] (system most closely resembling the one used in the current experiments), Wan & Krishnan [1986], Siddiqui *et al.* [1986] and Kawaji *et al.* [1991] are shown in Figures 2, 3, 4 and 5 respectively, predictions obtained using the Ardron & Banerjee [1986] flooding correlation are also shown in these figures. It can be seen that for the experiments of Krowlewski [1980], Siddiqui *et al.* [1986] and Kawaji *et al.* [1991] the predictions of the present model are in very good agreement with the experimental results and in fact better than those obtained using the Ardron & Banerjee [1986] flooding correlation. This correlation does however produce a better agreement with the experiments of Wan & Krishnan [1986] than the CCFL model developed as part of the current research. The comparisons with the experimental results of both Wan & Krishnan [1986] and Kawaji *et al.* [1991] are only carried out over part of the region of the data. The reason for this is that both authors state that at large values of $J_l^{*1/2}$ the flow remains supercritical throughout the horizontal leg. Under these conditions neither the present CCFL model nor the Ardron & Banerjee [1986] flooding correlation are applicable since in both cases flooding is associated with the presence of a hydraulic jump.

The standard deviations of the predictions with respect to the experimental results which are given by:

$$\sigma = \sqrt{\frac{1}{N}\sum\left(X_{calc} - X_{exp}\right)^2} \quad ,\psi \tag{14}$$

are presented in Table 1 for all the cases that were studied . It can be seen that the standard deviations of the present model are lower than those for the Ardron & Banerjee [1986] flooding correlation for four of the five cases where this correlation was applicable, the only exception being the results of Wan & Krishnan [1986](Fig. 3).

The prediction of the flooding point using this model for all of the orifice ratios studied in this project (β=0.90, 0.83, 0.77, 0.72, 0.66 and 0.55) are shown in Figures 6–11. It should be pointed out that to the best of the authors knowledge there are no models available in the open literature which are capable of predicting the flooding point occuring in an elbow between a vertical and a horizontal leg in which an orifice is placed. It can be seen that in general the agreement between the predicted and experimental flooding points is excellent. For the orifices having β ratios of 0.77, 0.72, and 0.66 for values of $J_l^{1/2}$ greater than 0.35 it can be seen that there is a change in the slope of the experimental results which is not predicted by the current model. The current model predicts the onset of flooding as being due to the inception of entrainment at the crest of a hydraulic jump occuring inside the elbow. For high liquid flow rates, both Wan & Krishnan [1986] and Kawaji [1989] found that the hydraulic jump was shifted towards the exit of the horizontal leg and flooding was due to slugging at this point. The results of both these researchers exhibit a change in slope at the highest liquid flow rates similar to that observed in the current results. If the phenomena which leads to flooding, at the highest liquid flow rates, is not the one represented by the phenomenological model, it will not be surprising if the model fails to capture the change in slope seen in the experimental results.

A comparison of the predictions of the model against the experimental results of Kawaji [1993] for orifices of (β=0.865, 0.67 and 0.55) are shown in Figures 12–14. In general, the agreement between the predictions and the experimental results is excellent. At the highest dimensionless liquid superficial velocities for the $\beta = 0.865$ case were Kawaji's data exhibits an unusual trend of the dimensionless superficial gas velocity at flooding being almost constant the predicted and experimental results do however diverge.

5.- Conclusions

It can be seen that in general the present model does a very good job of predicting the flooding which occurs in an elbow between a vertical and a horizontal leg. In fact for the case without an orifice the model is in a majority of the cases studied in better agreement with the experimental results than the only other correlation which is available in the open literature that of Ardron & Banerjee [1986]. For the cases in which an orifice is placed in the horizontal leg the predictions of the flooding points for a wide range of orifice sizes are in good agreement with the experimental results obtained both in our laboratory and by other researchers. It must also be emphasized the that to the best of the authors knowledge this is the only model available which is capable of predicting the flooding point occuring in an elbow between a vertical and a horizontal leg in which an orifice is placed.

Acknowledgments

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Nomenclature

a	Wave amplitude (m).
A	Cross sectional area (m^2).
C_d	Drag coefficient.
C_s	Interfacial shape coefficient.
D	Diameter (m).
f_i	Interfacial friction factor.
F_d	Drag force (N).
F_σ	Retaining force (N).
Fr	Froude number.
g	Acceleration due to gravity (m/s^2).
h	Height (m).
J	Superficial velocity (m/s).
$\dot{m}$	Mass flow rate (kg/s).
Q	Volumetric flow rate (m^3/s).
v	Velocity (m/s).
α	Void fraction.
β	Orifice ratio ($= D_{orifice}/D_{tube}$).
δ	Film thickness (m).
μ	Viscosity (Ns/m^2).
ν	Kinematic viscosity (m^2/s).
ρ	Density (kg/m^3).
τ_i	Interfacial shear stress (N/m^2).

Subscripts and Superscripts

c	critical.
h	horizontal.
j	jump.
l	liquid.
g	gas.
$*$	non dimensional quantity.

Experiments	Model	Standard Deviation
IGN $\beta = 1$	IGN	0.036
IGN $\beta = 1$	Ardron & Banerjee [1986]	0.043
IGN $\beta = 0.90$	IGN	0.050
IGN $\beta = 0.83$	IGN	0.048
IGN $\beta = 0.77$	IGN	0.046
IGN $\beta = 0.72$	IGN	0.032
IGN $\beta = 0.66$	IGN	0.033
IGN $\beta = 0.55$	IGN	0.021
Krowlewski [1980]	IGN	0.042
Krowlewski [1980]	Ardron & Banerjee [1986]	0.096
Siddiqui *et al.* [1986]	IGN	0.019
Siddiqui *et al.* [1986]	Ardron & Banerjee [1986]	0.044
Wan & Krishnan [1986]	IGN	0.038
Wan & Krishnan [1986]	Ardron & Banerjee [1986]	0.013
Kawaji *et al.* [1991]	IGN	0.018
Kawaji *et al.* [1991]	Ardron & Banerjee [1986]	0.026
Kawaji *et al.* [1993] $\beta = 0.865$	IGN	0.157
Kawaji *et al.* [1993] $\beta = 0.67$	IGN	0.029
Kawaji *et al.* [1993] $\beta = 0.55$	IGN	0.023

Table 1: Standard Deviation of Model Predictions vs. Experiments.

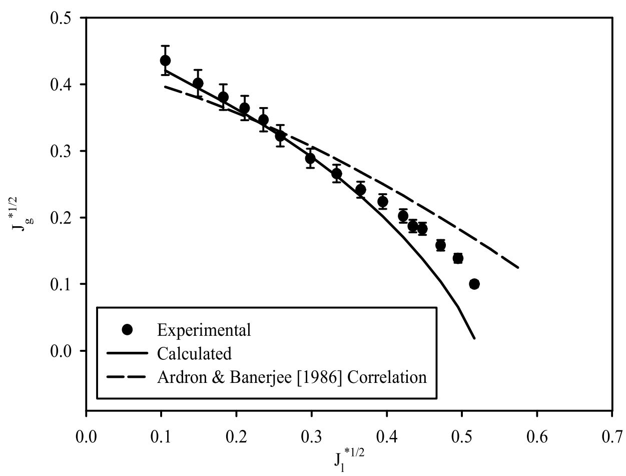

Figure 1. Comparison of predicted and experimental flooding points IGN experiments (no orifice).

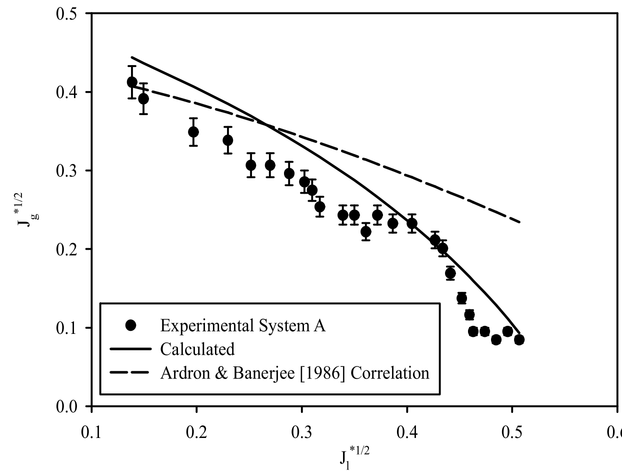

Figure 2. Comparison of predicted and experimental flooding points experiments of Krowlewski [1980].

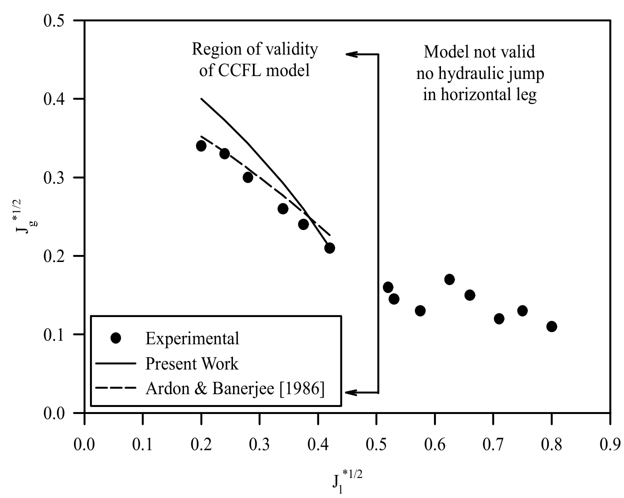

Figure 3. Comparison of predicted and experimental flooding points experiments of Wan & Krishnan [1986].

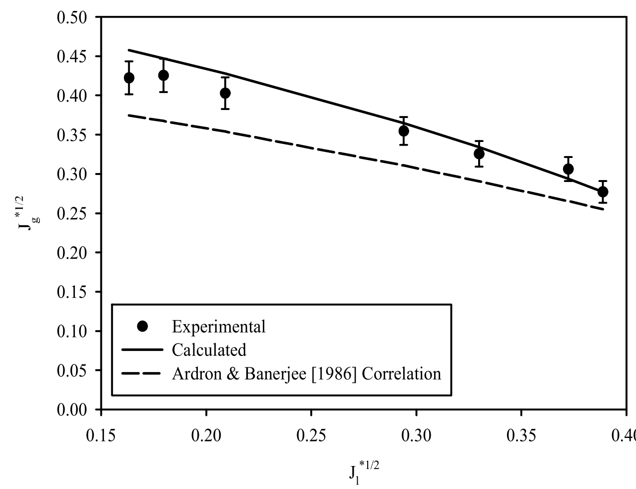

Figure 4. Comparison of predicted and experimental flooding points experiments of Siddiqui *et al.* [1986].

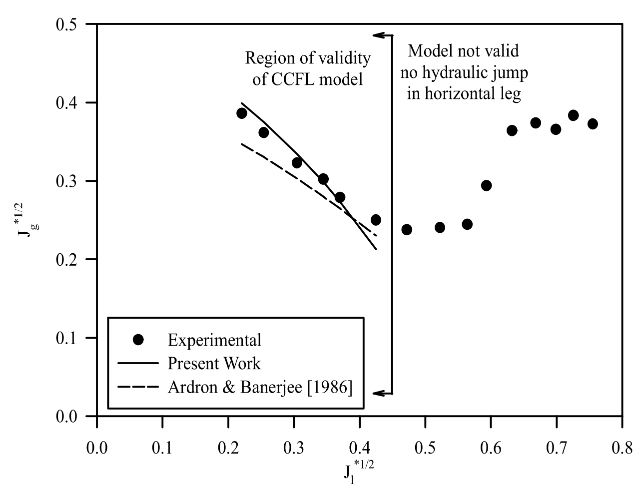

Figure 5. Comparison of predicted and experimental flooding points experiments of Kawaji *et al.* [1991]

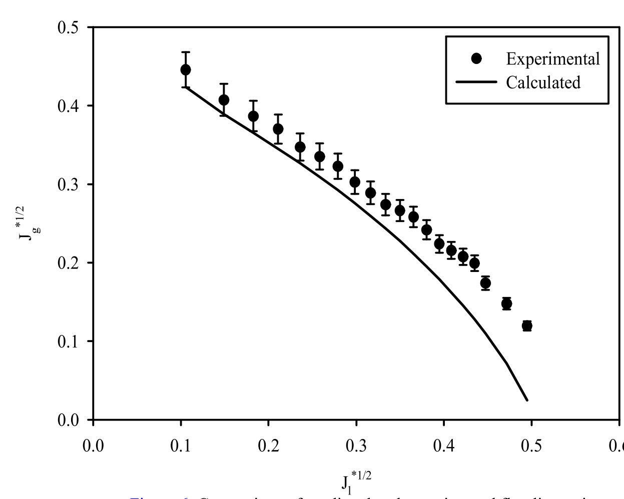

Figure 6. Comparison of predicted and experimental flooding points IGN experiments (Orifice β=0.90).

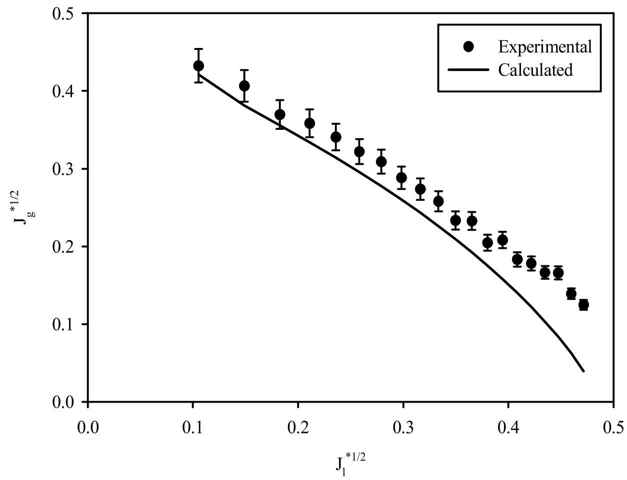

Figure 7. Comparison of predicted and experimental flooding points IGN experiments (Orifice β=0.83).

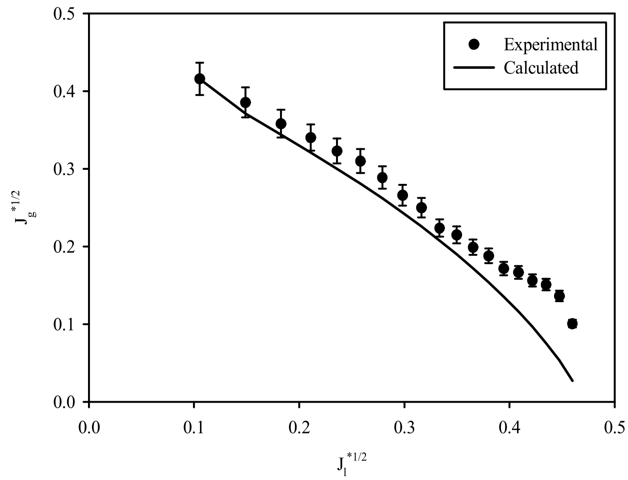

Figure 8. Comparison of predicted and experimental flooding points IGN experiments (Orifice β=0.77).

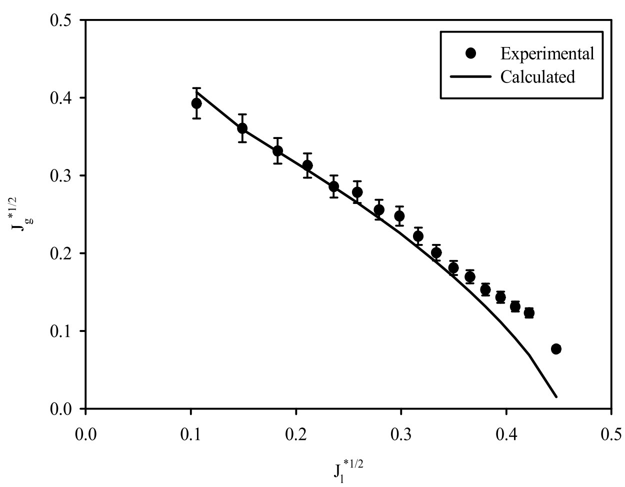

Figure 9. Comparison of predicted and experimental flooding points IGN experiments (Orifice β=0.72).

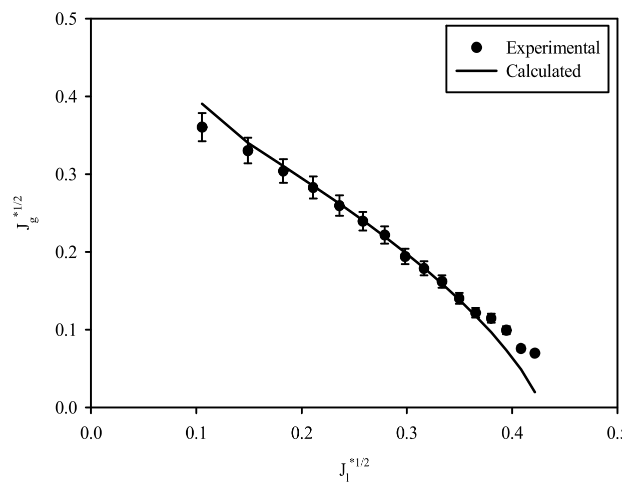

Figure 10. Comparison of predicted and experimental flooding points IGN experiments (Orifice β=0.66).

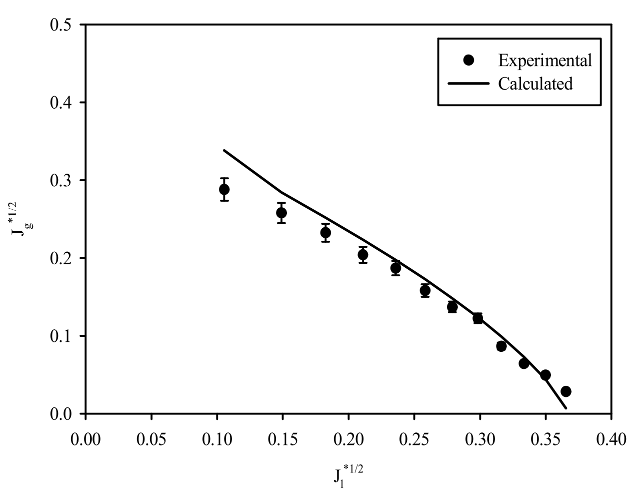

Figure 11. Comparison of predicted and experimental flooding points IGN experiments (Orifice β=0.55).

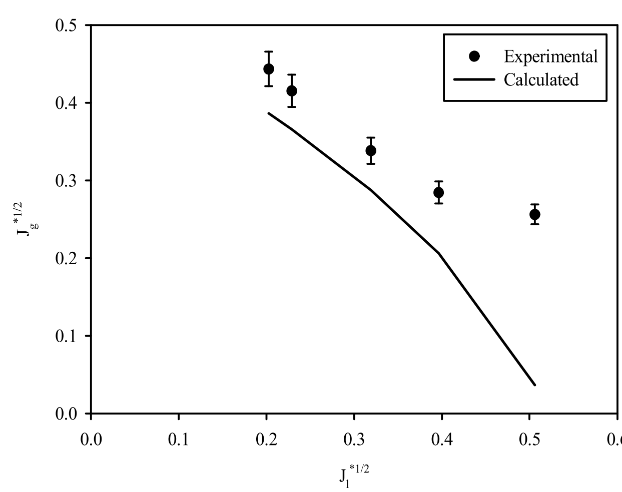

Figure 12. Comparison of predicted and experimental flooding points experiments of Kawaji *et al.* [1993] (Orifice β=0.865).

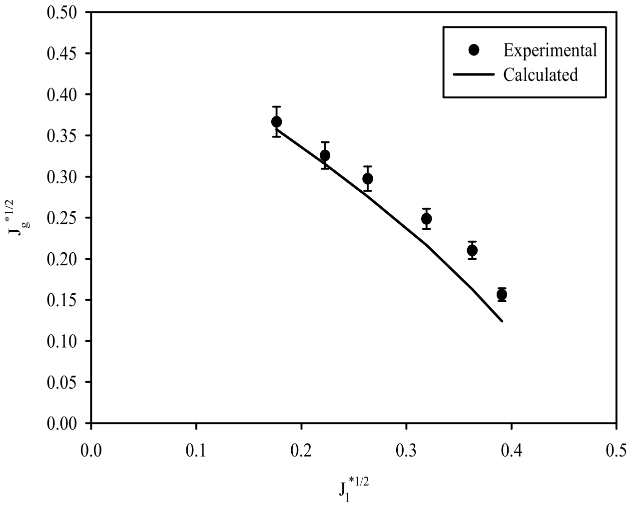

Figure 13. Comparison of predicted and experimental flooding points experiments of Kawaji *et al.* [1993] (Orfice β=0.67)

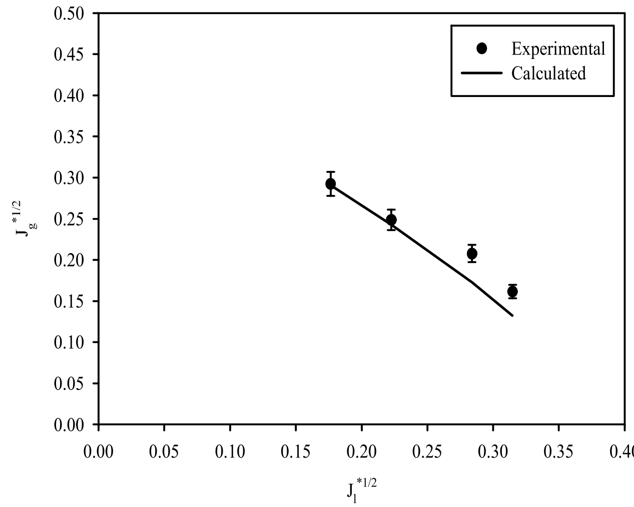

Figure 14. Comparison of predicted and experimental flooding points experiments of Kawaji *et al.* [1993] (Orifice β=0.55).