Int. J. Multiphase Flow Vol. 7, No. 6, pp. 647–658, 1981
Printed in Great Britain.

0301-9322/81/060647-12$02.00/0
Pergamon/Elsevier

# FLOODING IN TUBES AND ANNULI

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(*Received* 9 *March* 1981; *in revised form* 21 *May* 1981)

**Abstract**—The limitation of vertical countercurrent flow, called flooding, is important for the operation of Emergency Core Cooling Systems in Nuclear Reactors.

A new flooding correlation is presented which solves the obvious contradiction between the Wallis correlation and the study by Pushkina and Sorokin concerning the scaling question at zero penetration of liquid. In addition, this flooding correlation is applicable for partial delivery in pipe and annuli experiments as long as the liquid penetrates in the form of a film along the walls.

## 1. INTRODUCTION

The simultaneous flow of liquid downwards and gas upwards in a conduit has its limitations. The higher the gas flow rate, the lower is the possible liquid flow rate. The limit of this countercurrent flow is called "flooding"; it is of major importance in the connection with the operation of Nuclear Reactor Emergency Core Cooling Systems. Its accurate prediction is a significant aspect of analyzing the performance of these safety devices.

Past experiments on this subject have resulted essentially in two correlations. Of special interest is the work by Pushkina & Sorokin (1969). They performed experiments in various diameter tubes to evaluate the zero penetration point (no liquid down) as a function of pipe size. The conclusion from their work was that the gas velocity sufficient to prevent any liquid from penetrating downwards is constant and independent of the pipe size (at least for pipe diameters 0.15 m and above).

The other correlation describing not only the minimum gas velocity for zero liquid penetration but also the delivery of liquid as a function of the gas flow rate is from Wallis (1969). This correlation derived from experiments in small pipes, predicts the gas velocity for zero penetration to be proportional to the square root of the diameter, thus increasing with pipe size.

The two correlations contradict each other when used in the same geometry range. The former one predicts no geometric dependency of the gas flow rate for zero liquid penetration while the latter one does.

The analysis presented here resolves this contradiction and shows that both previously mentioned correlations are valid but each one only in a certain geometry range as was already supposed by Wallis & Makkenchery (1974).

An analysis for flooding is presented which unifies the whole geometry range in one equation and is applicable not only for zero penetration but for partial delivery of liquid as well. The only limitation to this theory is the assumption that the predominant liquid penetration occurs in the form of a liquid film along the walls of the conduit. This theory can also be applied to predict the flooding behavior in annuli, which is important for nuclear reactor safety considerations. This theoretical analysis shows good agreement with experiments performed in pipes and annuli by Richter *et al.* (1979), Richter & Murphy (1979), and Richter & Wallis (1979). Predictions about the pressure drop can also be derived from this analysis.

## 2. TECHNICAL BACKGROUND

There is a limitation to the flow rates of gas and liquid flowing countercurrently in a vertical conduit, i.e. if the gas flow rate is increased to a certain value it limits the downward liquid flow rate. This is called flooding. At each particular gas flow rate there is a maximum liquid flow rate and vice versa (see figure 1).

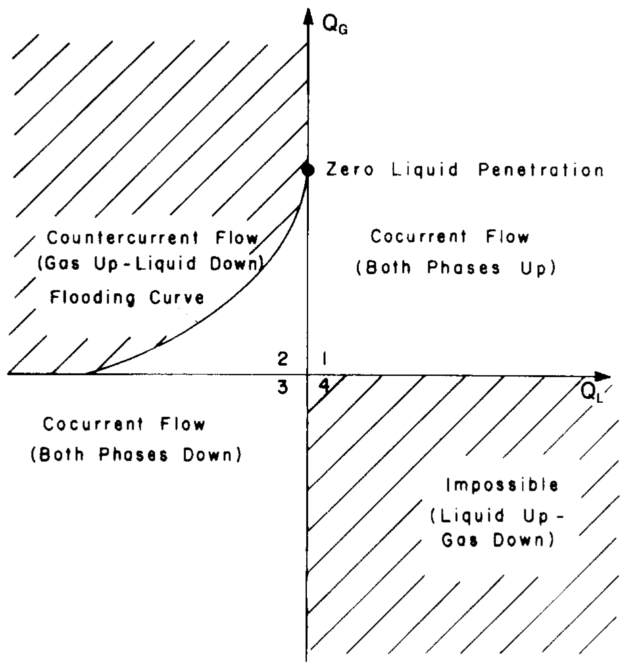


Fig. 1. Two-phase flow in vertical conduits (the second quadrant represents countercurrent flow).

Essentially, two flooding correlations have emerged from experiments of different researchers, Pushkina & Sorokin (1969), Wallis (1969). One equation correlates the gas flux vs. the liquid flux under flooding conditions (Wallis correlation):

$$j_G^{*1/2} + m j_L^{*1/2} = C \qquad [1]$$

$m$ and $C$ are constants and $m$ can be set approximately to unity for two-component systems when there is no mass transfer between the two-phases. $C$ is dependent upon entrance conditions and ranges usually between $C = 0.7$ and $C = 1.0$. $j_G^*$ and $j_L^*$ are dimensionless fluxes of gas and liquid in the countercurrent flow region. The dimensionless gas flux is

$$j_G^* = \frac{\rho_G^{1/2} j_G}{[gD(\rho_L - \rho_G)]^{1/2}}. \qquad [2]$$

$j_G$ represents a superficial velocity; it is the gas flow rate divided by the total flow cross section. $D$ is the diameter of the test section tube; in experiments in annuli it is assumed to be the average circumference. In the latter case the lower case $j_G^*$ is normally replaced by a capital $J_G^*$. In the liquid flux the subscripts $G$ in [2] on the lefthand side and in the numerator on the righthand side are replaced by the subscript $L$.

The second correlation for flooding deals only with one extreme case, namely zero liquid penetration, Pushkina & Sorokin (1969) (see figure 1). This theory assumes that a constant Kutateladze number predicts the lowest gas flux for zero penetration successfully

$$Ku = \frac{\rho_G^{1/2} j_G}{[g\sigma(\rho_L - \rho_G)]^{1/4}} \qquad [3]$$

where $\sigma$ is the surface tension. The Kutateladze number is similar to $j_G^*$ presented in [2] but it contains instead of a physical geometric parameter of the test facility a geometric parameter representative of a wavelength

$$l = \left[\frac{\sigma}{g(\rho_L - \rho_G)}\right]^{1/2} \quad [4]$$

similar to a Taylor instability. Introducing this wavelength into [2] for the geometric parameter $D$, will result in [3]. Pushkina & Sorokin (1969) introduced the Kutateladze number and found that this number was constant at $Ku = 3.2$ for zero liquid penetration for different pipe sizes. This means that the superficial gas velocity has to be constant, since the Kutateladze number contains only physical properties and the superficial gas velocity.

Returning to [1] we would find for zero liquid penetration that

$$j_G^{*1/2} = C, \text{ thus}$$

$$j_G \propto D^{1/2}.$$

Introducing a nondimensional pipe diameter by dividing by the length parameter from [4] we get:

$$D^* = \frac{D}{l} = N_B^{1/2} = D\left[\frac{g(\rho_L - \rho_G)}{\sigma}\right]^{1/2} \quad [5]$$

where $N_B$ is the Bond number. Now we can plot the Kutateladze number vs. this nondimensional pipe diameter for zero penetration (see figure 2) for the two correlations in [1] and [3]. The nondimensional flux $j_G^*$ is related to the Kutateladze number through

$$Ku = j_G^* D^{*1/2}, \text{ or } j_G^* N_B^{1/4}. \quad [6]$$

The Wallis flooding correlation [1] suggests an increase of gas momentum with scale of the pipe for zero penetration if $C$ is a universal constant. The data employed in figure 2 for different pipe

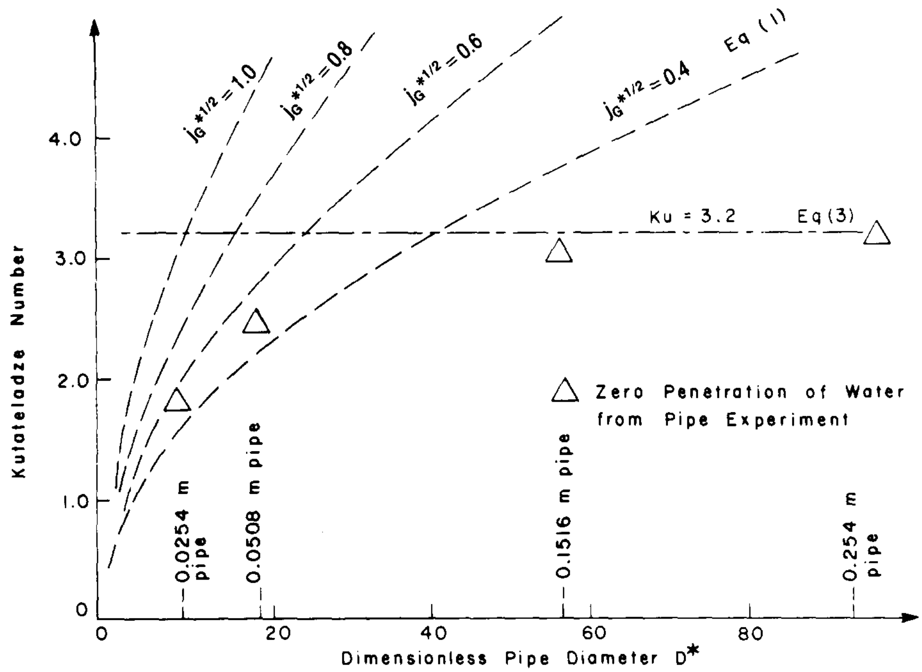


Fig. 2. Kutateladze number vs nondimensional geometric parameter and experimental results for zero penetration of liquid.

sizes were obtained in the same apparatus using different pipe sizes (diameters 0.0254, 0.0508, 0.152, and 0.254 m).

The test facility consisted of an upper and lower plenum. The gas was introduced into the lower plenum and was allowed to flow upwards through the test tube. A pool of water in the upper plenum above the upper end of the pipe provided the water for penetration. In the flooding experiments the pool height was adjusted until it did not influence the flooding behavior, Richter & Lovell (1977).

Figure 2 shows that neither the flooding correlation nor the Kutateladze number can predict zero penetration for all pipe sizes, rather the Wallis correlation is consistent with data for pipe sizes up to 0.0508 m dia. and the Kutateladze number $Ku = 3.2$ for pipe sizes larger than 0.152 m in diameter.

## 3. ANALYSIS

A theory was developed which assumes that the penetration of liquid in a pipe occurs in the form of a thin wavy film flowing along the walls (see figure 3). This was the predominant flow regime observed in the experiments.

For the control volume I (total cross section) in a round pipe, the force balance is

$$-\frac{dp}{dz}\frac{\pi D^2}{4} + \tau_W \pi D = [\rho_L(1-\alpha) + \rho_G \alpha] g \frac{\pi D^2}{4} \qquad [7]$$

with $\alpha$ the void fraction of the gas and $\tau_W$ the wall shear stress. For the control volume II (see figure 3) which includes only the gas phase we have:

$$-\frac{dp}{dz}\frac{\pi D^2}{4}\alpha - \tau_i \pi D \sqrt{(\alpha)} = \rho_G g \frac{\pi D^2}{4}\alpha \qquad [8]$$

with $\tau_i$ the interfacial shear stress. We can eliminate the pressure drop from [7] and [8] and

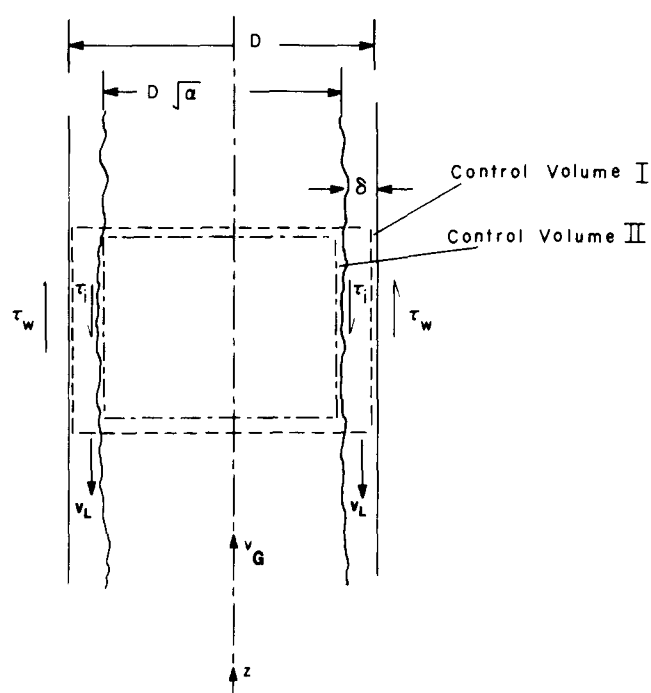


Fig. 3. Momentum balance in a pipe countercurrent flow.

eventually we get:

$$\frac{4\tau_w}{D} + \frac{4\tau_i}{D\sqrt{(\alpha)}} = (\rho_L - \rho_G)g(1-\alpha) \qquad [9]$$

For the wall shear stress we will introduce, assuming $v_f$ to be the average liquid velocity

$$\tau_w = \frac{1}{2} C_w \rho_L v_L^2 = \frac{1}{2} C_w \frac{\rho_L j_L^2}{(1-\alpha)^2} \qquad [10]$$

with $C_w$ the wall friction factor. For the interfacial shear stress we get:

$$\tau_i = \frac{1}{2} C_i \rho_G (v_G + v_i)^2 \qquad [11]$$

where $v_i$ is the liquid velocity downward at the interface and $C_i$ the interfacial friction factor.

Since the gas flows upwards, the interaction at the interface will slow down the interfacial velocity $v_i$. At sufficiently high gas velocities the liquid velocity at the interface might even be cocurrent with the gas velocity. We have assumed that $v_i \ll v_G$ and can therefore be neglected in [11].

To determine the interfacial friction factor, we will adopt the correlation from the "wavy" annular theory from Wallis (1969). This is possible for countercurrent flow since we have neglected the interfacial velocity compared to the gas velocity. Wallis found that

$$C_i = C_w \left(1 + 300 \frac{\delta}{D}\right) \qquad [12]$$

and this interfacial friction factor represents a good agreement with data, where $\delta$ is the average film thickness. It is interesting to note that [12] is similar to Nikuradse's rough pipe correlation (Wallis 1969)

$$C_{wr} \simeq C_w \left(1 + 75 \frac{k_s}{D}\right) \qquad [13]$$

with $k_s$ the sand roughness of the pipe, indicating that the waviness of the liquid film is about four times the average film thickness. Hewitt & Nicholls (1969) evaluated in their annular two-phase flow studies the ratio of wave height to film thickness and found it to be between 4 and 6. The void fraction of the liquid can be described as:

$$(1-\alpha) = \frac{4\delta}{D}\left(1 - \frac{\delta}{D}\right) \qquad [14]$$

for larger pipes or for thin films, a good approximation is

$$(1-\alpha) \simeq \frac{4\delta}{D}. \qquad [15]$$

In the case of little interfacial shear stress $\tau_i \ll \tau_w$ we can evaluate from [9], [10] and [15]:

$$\frac{\delta}{D} = \left(\frac{C_w}{32}\right)^{1/3} j_L^{*(2/3)} \qquad [16]$$

and for the void fraction of the liquid:

$$(1-\alpha)=(2C_w)^{1/3}j_L^{*(2/3)}. \qquad [17]$$

Wallis (1969) found that by comparison with experiments

$$\frac{\delta}{D}=0.063\,j_L^{*(2/3)} \qquad [18]$$

by comparing [16] and [18] we get a wall friction factor of approximately:

$$C_w=0.008$$

Since this value is in better agreement with experiments, it will be used from now on.

The amplitude of the wave, $\delta_L'$ can be evaluated as a function of the pressure difference between the crest of the wave and the base assuming that the wave has a semicircular shape (see figure 4). It is assumed that the pressure difference between the bottom of the wave and the crest is the dynamic head of the gas flow. For the wave to be stable this pressure difference has to be balanced by surface tension. Thus we get:

$$\frac{1}{2}\rho_G v_G^2 \leqq \frac{\sigma}{\delta_L'} \qquad [19]$$

otherwise the wave becomes unstable and disintegrates. Droplets from the wave will be carried with the gas counter-current to the liquid flow, thereby limiting the liquid flow downward.

From the considerations of the interfacial friction factor we concluded that $\delta_L' \simeq 4\delta$, thus we can compute the average film thickness from [19]

$$\delta \leqq \frac{\sigma}{2\rho_G v_G^2} \qquad [20]$$

For large diameter tubes and very thin films we can approximate $v_G \simeq j_G$, thus with [9]–[20] we can develop a new flooding correlation. Employing [2] as well, we will eventually get

$$\frac{C_w}{4}N_{B}^3 j_G^{*6} j_L^{*2}+C_w N_b j_G^{*4}+150\;C_w j_G^{*2}=1 \qquad [21]$$

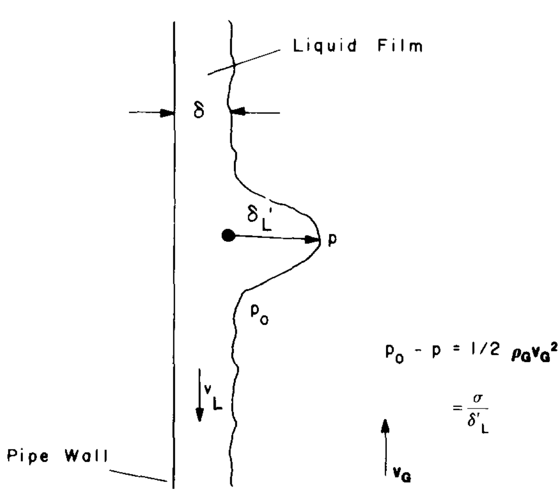


Fig. 4. Waviness of film in countercurrent flow.

All terms in [21] are made nondimensional by dividing through the gravitational pressure drop. The first term represents the pressure drop due to wall friction, the second term is the pressure drop at the interface if it is smooth. The third term describes the pressure drop due to a wavy interface.

The correlation [21] was compared with experiments of flooding in tubes of different sizes by Wallis & Makkenchery (1974). Figure 5 shows that the agreement with (21) overpredicts penetration rates for very small pipes, even if we use the exact value for the void fraction of the liquid, thus use [14] instead of [15] in the development of the flooding correlation. This flooding correlation is predicting the behavior in small pipes very well only if we assume arbitrarily that the waviness of the film is a factor of 4 smaller thus $\delta_L' \simeq \delta$, [20].

For zero penetration we have $j_L^* = 0$ and thus from [21] for the gas flux:

$$j_G^{*(1/2)} = -\frac{75}{N_B}\left[1 - \left(1 + \frac{N_B}{75^2 C_w}\right)^{1/2}\right] \qquad [22]$$

It is interesting to study the two extremes of the solution in [22].

(a) $(N_B/75^2 C_w) < 1$ (valid for small pipes), we can approximate:

$$\left(1 + \frac{N_B}{75^2 C_w}\right)^{1/2} \simeq 1 + \frac{1}{2}\frac{N_B}{75^2 C_w}.$$

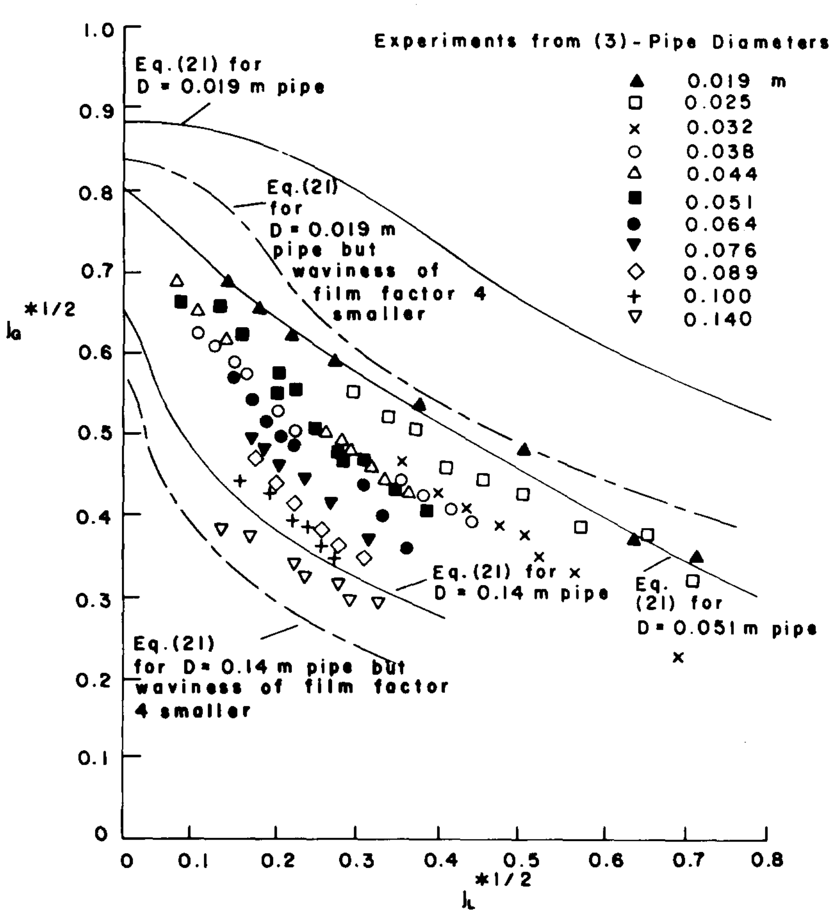


Fig. 5. Comparison of new flooding correlation with pipe experiments from Wallis & Makkenchery (1974).

Introducing this into [22] we get:

$$j_G^{*1/2} = \left(\frac{1}{150C_w}\right)^{1/4} = 0.96 \quad [23]$$

which is similar to the Wallis solution, giving:

$$j_G^{*1/2} = C \text{ with } C = 0.7 \text{ to } 1.0.$$

(b) $(N_B/75^2C_w) > 1$ (valid for large pipes), we can approximate:

$$\left(1 + \frac{N_B}{75^2C_w}\right)^{1/2} \approx \left(\frac{N_B}{75^2C_w}\right)^{1/2}$$

and introducing this into [22] we get:

$$j_G^* = \frac{1}{N_B^{1/4}C_w^{1/4}} \quad [24a]$$

or

$$Ku = j_G^* N_B^{1/4} = \left(\frac{1}{C_w}\right)^{1/4} = 3.3 \quad [24b]$$

which is very close to the value obtained by Pushkina & Sorokin (1969).

The result in [24b] is very interesting. The Kutateladze number contains gas inertia, buoyancy and surface tension. Here it is shown that it is just the fourth root of the inverse of the wall friction factor. The correlation presented in [21] gives the Wallis (1969) solution for small pipes and the Pushkina & Sorokin (1969) solution for large pipes.

Figure 6 is similar to figure 2 but contains this new correlation in addition. The agreement with pipe data over the complete diameter range is improved substantially.

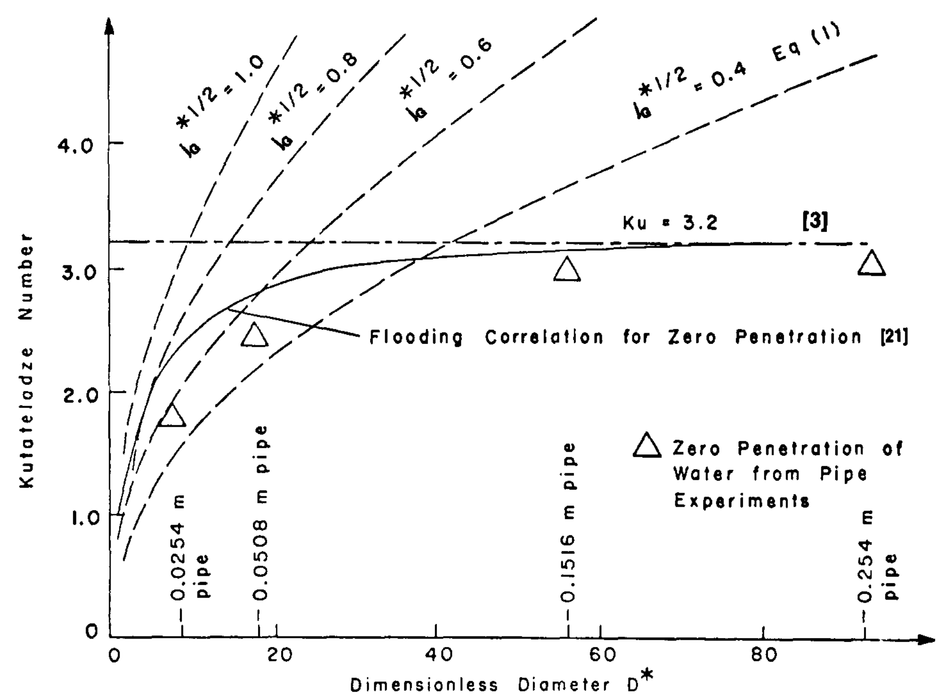


Fig. 6. Kutateladze number vs nondimensional geometric parameter. Experimental results and new flooding correlation for zero penetration of liquid.

This new analysis is only concerned with the interaction at the interface not with dependency of flooding on the entrance conditions. In addition, it is assumed that the liquid velocity at the interface is essentially zero, which is certainly not valid for high penetration rates.

## 4. PRESSURE DROP IN COUNTERCURRENT FLOW

Countercurrent flow shows three distinct regions of flow behavior:

*Region I.* High penetration rate of water. The interface appears to be smooth, thus the interfacial shear stress is probably small. In this region the pressure drop is very small since the weight of the liquid film is essentially balanced by the wall shear stress. The liquid flux and with it the liquid void fraction decreases as the gas flux is increased (see figure 7).

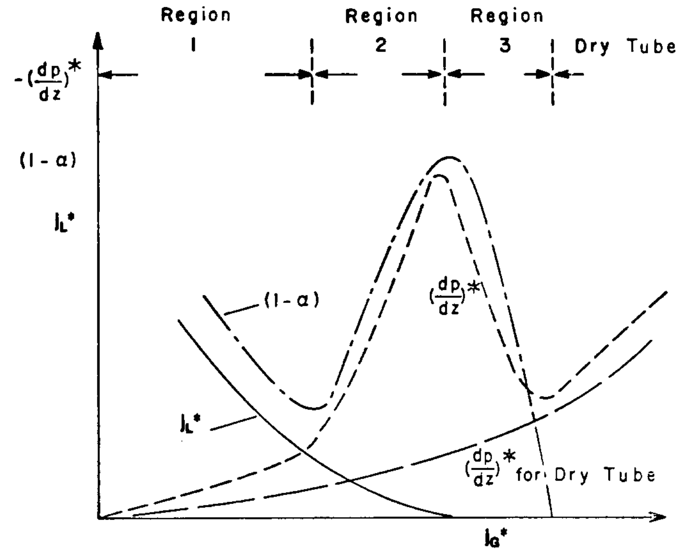


Fig. 7. Pressure drop and void fraction during flooding in a vertical tube, Bharathan (1979).

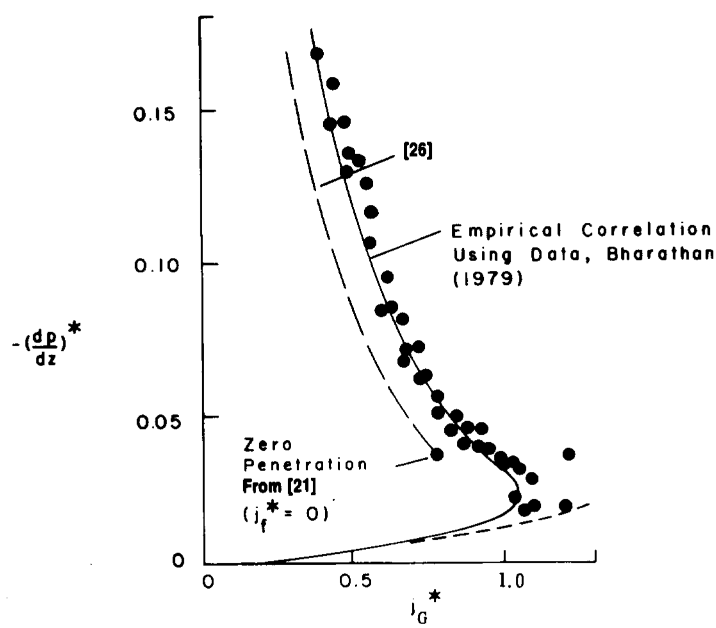


Fig. 8. Pressure gradient vs gas flux for 0.025 m tube ($D^* = 9.4$): ●, two-phase data; ——, two-phase prediction; ---, single-phase prediction; —–—, [26].

*Region II.* The liquid penetration is decreasing with increasing gas flux. The film is very wavy and unstable in the tube. The wall shear stress and the interfacial shear stress are both important. The interfacial shear stress is increasing, thus it can support a thicker liquid film. Thus liquid void fraction and the pressure drop are increasing.

*Region III.* Small liquid penetration occurs. If we rearrange [7] we will eventually receive:

$$-\frac{\mathrm{d}p}{\mathrm{d}z}=(\rho_L-\rho_G)(1-\alpha)g+\rho_G g-2C_w\frac{\rho_L j_L^2}{(1-\alpha)^2 D} \qquad [25]$$

defining a nondimensional pressure drop and employing [2] for the nondimensional flux and [15], [20] for the void fraction we obtain eventually:

$$-\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)^*=-\frac{\mathrm{d}p/\mathrm{d}z}{(\rho_L-\rho_G)g}=\frac{2}{N_B j_G^{*2}}+\frac{\rho_g}{(\rho_L-\rho_G)}-\frac{1}{2}C_w N_B^2 j_L^{*2} j_G^{*4}. \qquad [26]$$

In this region the liquid void fraction as well as the pressure drop decreases with the increase in gas flux. This analysis can predict the trend for the pressure drop qualitatively very well. This is shown by comparison with experimental results by Bharathan (1979) in figure 8.

With further increase, the upward gas flow is capable of blowing the liquid film out at the top cocurrently with the gas, thus the liquid film thickness, the void fraction and the pressure drop decrease.

## 5. FLOODING IN ANNULI

Of special interest for Nuclear Reactor Safety consideration is the flooding behavior in the downcomer of a pressurized water reactor, which is in the form of an annulus. Many scaled down experiments have been performed of study flooding in annuli, Richter & Wallis (1979), Richter & Murphy (1979), Flanigan *et al.* (1975), and Crowley *et al.* (1976). The theory developed in the paper can be applied to an annulus as well. We introduce an average circumference of the annulus, $w$, and define the dimensionless gas flux with:

$$J_G^*=\frac{\rho_G^{1/2} j_G}{[gw(\rho_L-\rho_G)]^{1/2}} \qquad [27]$$

and the liquid flux accordingly.

The liquid void fraction in an annulus is:

$$(1-\alpha)=\frac{2\delta}{S} \qquad [28]$$

where $\delta$ is the liquid film thickness and $S$ the gap size. This is only valid if $\delta \ll S$. The ratio of the gap size to the average circumference is:

$$S^*=\frac{S}{w}. \qquad [29]$$

If different size reactor vessels are used for verification of the flooding behavior in different geometric scales the parameter $S^*$ should be a constant, if gap size and circumference are scaled linearly.

The same force balance is used for the annulus as previously for the pipe (see figure 3). For the liquid void fraction, [28] was introduced.

Using the same criterion as before for the average film thickness, the stability of the waves and the shear stresses, we obtain eventually for the flooding correlation in annuli:

$$C_w N_B'^3 J_G^{*6} S^{*2} J_L^{*2} + C_w N_B' J_G^{*4} + 150\, C_w \frac{J_G^{*2}}{S^*} = 1 \qquad [30]$$

All terms in [30] are made nondimensional by dividing through the gravitational pressure drop. The first term in [30] represents the pressure drop due to wall friction. The second term is the pressure drop due to friction at the interface, if this interface is smooth. Finally, the third term describes the pressure drop due to the wavy interface. $N_B'$ is the Bond number with the average circumference as the geometric length instead of the pipe diameter.

For zero penetration $J_L^* = 0$ we obtain:

$$j_G^{*2} = -\frac{75}{N_B' S^*}\left[1 - \left(1 + \frac{N_B' S^{*2}}{75^2 C_w}\right)^{1/2}\right]. \qquad [31]$$

Again we have two extremes, the one if the last term in [31] is smaller than 1:

$$J_G^{*1/2} = \left(\frac{S^*}{75^2 C_w}\right)^{1/4} = 0.41$$

if the proper geometrical scaling laws are used. (In these considerations it was assumed that a full scale reactor has a gap width of 0.25m and a circumference of 14.4m.) The value is in good agreement with the result of Crowley *et al.* (1976). They found that zero penetration occured at:

$$J_G^{*1/2} = 0.4$$

in their small scale experiments.

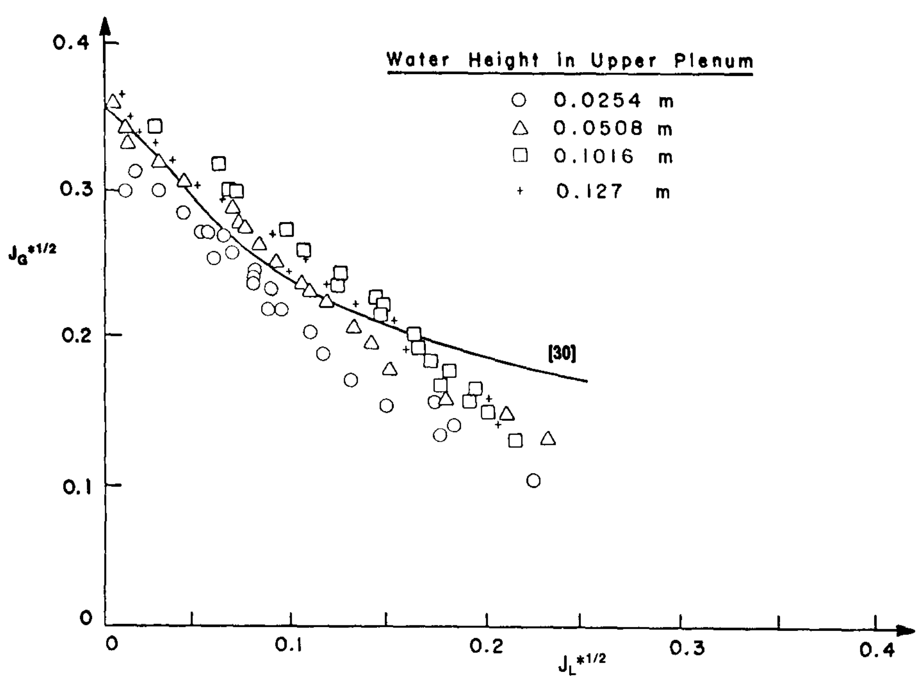


Fig. 9. Nondimensional gas flux vs water flux for flooding in a 2/15 scale of a nuclear reactor annulus. Different water heights in upper plenum.

If the last term in [31] is much larger than 1 then the solution results in:

$$Ku = J_G^* N_B^{(1/4)} = \left(\frac{1}{C_w}\right)^{1/4} = 3.3$$

Collier *et al.* (1978) obtained $Ku = 3.2$ for larger scale experiments. The flooding correlations for annuli from [30] also shows good agreement for the region of partial delivery as shown in figure 9.

## 6. CONCLUSION

An analysis of flooding has been presented, which resolves the obvious problems with previously presented correlations which are limited to certain geometries. It is capable of not only providing useful information about zero penetration, but also for the partial delivery of liquid. In addition, the pressure drop can be estimated in certain regions of flooding. The only assumption is the liquid penetration in the form of a uniformly distributed film along the wall. This assumption might be in question if during partial delivery water penetrates the annulus on one side while steam might escape on the other.

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