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TWO-PHASE REDISTRIBUTION IN HORIZONTAL SUBCHANNEL FLOW—TURBULENT MIXING AND GRAVITY SEPARATION

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Abstract—The redistribution of two-phase flow in two horizontal interconnected subchannels caused by gravity separation and turbulent mixing has been investigated experimentally using an air-water loop. The measured redistribution data included the axial distribution of void fraction and liquid and gas flow rates in the two subchannels. The redistribution data exhibited an asymptotic behaviour, approaching certain flow distributions independent of the inlet distribution. The observed equilibrium distributions were explained as a balance between gravity forces (which tend to cause flow stratification) and turbulent diffusion (which tends to homogenize the two-phase mixture). A constitutive equation for transverse vapour drift, to account for both gravity separation and turbulent diffusion, was presented and a turbulent mixing coefficient was identified. The experimental data were used to obtain the best estimate of the empirical constants.

1. INTRODUCTION

In the last two decades, major efforts have been devoted to the development of techniques to allow the analysis and predictions of the thermal-hydraulics of coolant flow in nuclear reactor fuel channels. These efforts were motivated by the need to predict the occurrence of critical heat flux (CHF) at any location in the fuel assembly. Improving the accuracy of CHF prediction has important implications in determining various reactor operating limits. For example, accurate CHF prediction is a main criterion in determining normal operating conditions and the maximum allowable overpower during a power transient. Since the critical heat flux is a local phenomenon, accurate prediction of the local velocity and temperature fields within the nuclear reactor fuel channel is necessary. However, solving the field equations to yield local flow conditions is not possible, at the moment, due to the complexity of the geometry, lack of appropriate constitutive laws required for closure, particularly in the two-phase flow situation, as well as the required computer storage. Subchannel analysis is a compromise between the need for more details than that obtained through a lumped approach and practicality.

In subchannel analysis, as shown by Weisman & Bowring (1975) and Rowe (1979), the flow area of the fuel bundle is divided into small sections, i.e. subchannels, which are the interconnected spaces between fuel elements. Each subchannel is divided axially into small control volumes within which fluid properties are taken at the mixed mean values and local flow conditions are represented by the average values of velocity, pressure, temperature, void fraction, etc. The conservation equations for axial flow in each subchannel are written in standard averaged form with extra terms to account for the exchange of mass, momentum and energy between adjacent subchannels in the transverse direction. A simplified transverse momentum equation is usually used so that a two dimensional solution may be obtained. In single phase flow, Rogers & Todreas (1968) showed that two transverse exchange mechanisms should be considered; (a) diversion cross flow, which is driven by the transverse pressure gradient and causes transfer of energy, momentum and mass across the fuel bundle, and (b) turbulent mixing, which occurs due to the instantaneous turbulent fluctuations with which no net mass exchange is incorporated, although it may result in a net exchange of energy and/or momentum between adjacent subchannels.

However, for two-phase subchannel flow, the transverse exchange phenomena are complicated by the existence of a second phase. Nevertheless, they can be decomposed into the same two components, namely, diversion cross flow and turbulent mixing as well as a third component to describe "void drift" as outlined by Lahey (1977). Although diversion cross flow and turbulent mixing in two-phase flow can still be defined as the exchange mechanisms due to, and in the absence of, a transverse pressure gradient respectively, the implications of the definition of turbulent mixing are different from the single phase flow situation. Unlike single phase flow, the pressure drop associated with two-phase flow in a channel is not a unique function of the mass flow rate. For example, for two-phase flow in two interconnected subchannels, given the total mass flow rate and overall quality, there are an infinite number of flow distributions that may yield equal axial pressure gradient in the two subchannels, i.e. liquid–gas mass exchange may take place while maintaining a zero transverse pressure gradient. In other words, turbulent mixing in two-phase subchannel flow may cause a net mass as well as momentum and energy exchange between adjacent subchannels. The void drift in two-phase subchannel flow is due to the strong tendency of the vapour phase to drift towards the more open, higher velocity subchannels which may result in a non-uniform distribution of voids across the fuel bundle even in vertical flow. Non-uniform void distributions have been observed by Gonzalez–Santals & Griffith (1972) for vertical flow in adjacent subchannels which are geometrically different. In modelling the combined effect of turbulent mixing and void diffusion in vertical subchannel flow, Lahey (1977) presented a diffusion model in which the net vapour exchange between adjacent subchannels is assumed to be proportional to the non-equilibrium void fraction gradient in the transverse direction. The equilibrium void distribution is defined as that, once attained, no further flow exchange (redistribution) is observed.

For flow in horizontal fuel channels, such as those of the CANDU nuclear reactors, two-phase flow distribution between different subchannels is further complicated by the effect of gravity separation which will result in non-uniform distributions with upper subchannels mostly having higher void fractions. Although several subchannel computer codes have been developed based on the aforementioned concepts, such as those given by Rowe (1973) and Bowring (1967), none of these codes is suitable for predicting the basic thermal-hydraulic characteristics of two-phase flow in horizontal fuel channels due to the lack of appropriate constitutive relationships for gravity separation and turbulent mixing.

In developing the appropriate constitutive relationships needed for the development of a subchannel code for horizontal fuel channels, fundamental experiments are needed to identify the basic mechanisms of interest. Since the phenomena of interest is very complicated, it is important to design simple and well controlled experiments to focus on one or more of the governing factors. Accordingly, the experiments presented herein are intended to investigate the exchange mechanisms caused by gravity separation and turbulent mixing. This is attained by ensuring that the mean transverse pressure difference between adjacent subchannels is always zero in order to eliminate the diversion cross flow effects. The phenomenon of the void drift taking place due to geometrical differences between adjacent subchannels is also eliminated by using identical subchannels. The work presented herein is part of an experimental program to support the development of a CANDU subchannel code.

2. EXPERIMENTAL PROGRAM

2.1 *Experimental facility*

The experimental facility consisted of an air–water loop with a horizontal test section which was divided into two identical subchannels placed one above the other. The main features of the test loop are shown in figure 1. Air and water flows into each of the two

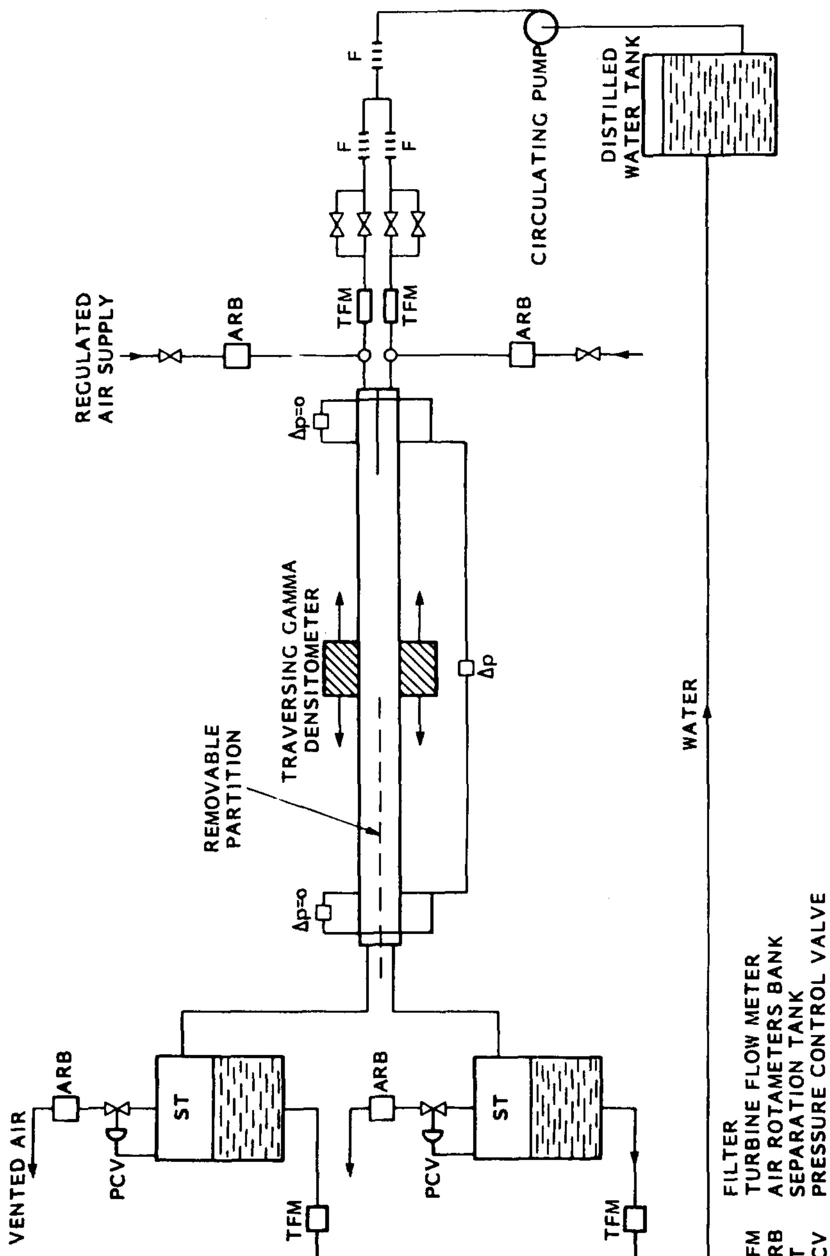

Figure 1. Schematic of the test loop.

subchannels were independently controlled. At the exit of the test section, the subchannel flows were split and discharged into two separation tanks. The water flows out of the separation tanks were fed to a holding tank and then back into the loop while the air was vented out to the atmosphere. The test section consisted of two subchannels separated from each other by removable partitions which allowed partial or total communication of the two subchannels. The test section had a typical fuel bundle geometry with a pitch to rod diameter ratio of 1.167 and the gap spacing between the rods equaled 2.5 mm. Further details of the experimental loop and test section were given by Shoukri *et al.* (1982a).

The required redistribution data included the axial variation of void fraction and air and water flow rates in each subchannel while the two subchannels are allowed to communicate along their entire length, i.e. the flow splitter is completely removed except at the exit. The axial variation of void fraction was measured using a traversing gamma densitometer system which was statically calibrated for the same channel geometry. However, the difficulty in measuring the axial variation of mass flow rates in each subchannel was overcome by changing the communication length, i.e. changing the flow splitter position, and measuring the exit flow. This was done for the communication lengths of 5, 10, 25 and 146 cm. Details of the instrumentation used are available in the reference by Shoukri *et al.* (1982a).

2.2 *Experimental procedures and test conditions*

As mentioned earlier, an important feature of the experiment was to ensure that transverse pressure difference between the two subchannels is zero along the communication length. In the experiments where equal air and water flow rates were introduced into the two subchannels, this condition was satisfied by maintaining equal pressures in the two separation tanks. For the experiments where unequal flow rates were introduced into the two subchannels, the condition of zero pressure difference was met by performing some preliminary tests. In these tests, the two subchannels were completely separated from each other. Both single-phase water and two-phase air–water pressure drop data were obtained along the test section. Knowing the pressure drop characteristics of the test section, a simple computer program was developed and used to calculate different combinations of inlet flows that would yield equal axial pressure gradient in the two subchannels for given total water and air flow rates. These predetermined combinations of air and water flow rates were then introduced into the two subchannels, while still completely separated. Some manipulation of the inlet air pressure regulators and inlet valving systems was then performed in order to achieve zero pressure difference between the two subchannels while the pressure in the separation tanks was set to equal pressures (mostly 130 KPa). This procedure was considered successful only when zero pressure difference between the two subchannels was achieved and constant water level in separation tanks was observed, i.e. the tanks were indeed at constant and equal pressures. It was found that these conditions were not possible to meet, with the present setup, for the conditions in which large differences in inlet flow quality between the two subchannels existed. These identified test conditions represent those in which zero pressure difference between the two subchannels existed along their entire length.

After identifying the test conditions, the length of the flow splitter was changed creating the required communication length. The inlet flows were adjusted to those predetermined values. When steady-state conditions were reached, as identified by the water level in the separation tanks, exit flow measurements were obtained and registered as the axial flows in the test section at the end of the specific communication length. The procedure was repeated for several communication lengths. The communication lengths used were 5, 10, 25 and 146 cm. The gamma densitometer was traversed axially, while the flow splitter is completely removed, to obtain the void fraction measurements in the two subchannels along the test section just before the beginning of the communication length and at 5, 8, 27, 56, 92 and 128 cm from the beginning of the communication length. The use of varying communication lengths to simulate the required measurements of flow rates at different axial positions was indirectly validated by comparing the void fraction measurements at a specific location (8 cm) when the communication length was 10, 25 and 146 cm. Good agreement was obtained.

The outputs from the pressure transducers were continuously monitored during experimentation to ensure that the zero pressure difference condition was always satisfied. Also, inlet and exit flow rates were used to check the mass balance which was found to be within $\pm 5\%$ for all runs.

Experiments were performed at three different mass fluxes, 950, 1360 and 1560 kg/m^{2}s.

2.3 *Experimental results*

As anticipated, significant upward gas drift, caused by gravitational effects, was observed in most of the experimental runs. Since zero transverse pressure difference between the two subchannels was always maintained during all the experiments reported herein, the net gas transfer to the upper subchannel was consistently accompanied by a simultaneous net liquid transfer to the bottom subchannel. From all of the 110 experiments performed, it was obvious that the distribution of the measured void fraction in the two subchannels followed closely, and was consistent with the observed gas–liquid exchange. Detailed listing of all the experimental results was given by Shoukri *et al.* (1982a). The results for three different experiments in which the same total liquid and gas flow rates were introduced into the test section with different inlet distributions are shown in figures 2–4. The results for equal inlet flow distribution are shown in figure 2 while figures 3 and 4 present the data for unequal inlet distribution in a reversed fashion, i.e. gas and liquid

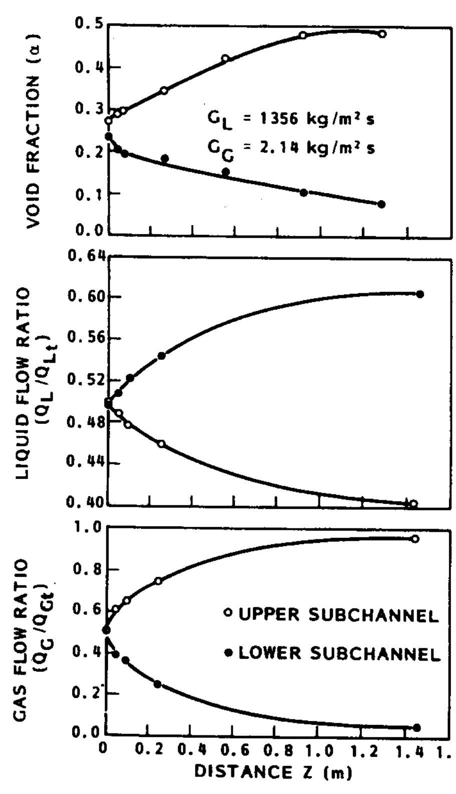

Figure 2. Redistribution results.

flows into the lower subchannel in figure 3 are the same as those of the upper subchannel in figure 4 and vice versa. The redistribution results at the same flow quality but at a lower mass flux are shown in figure 5. The features of the data shown in figures 2–5 are typical of all the experimental data obtained in this investigation.

The redistribution data showed that the rate of gas and liquid transfer between the two subchannels was high at the beginning of the communication length and decreased with increasing communication length. As the communication length increased, the redistribution data showed an asymptotic behaviour, approaching a certain flow distribution. The asymptotic distribution, or equilibrium distribution, can be defined as the distribution which, once attained, no further net flow exchange between subchannels is observed. By examining the results shown in figures 2–4, for the same total liquid and gas flow rates but for different inlet distributions, it can be revealed that the two-phase flow is approaching the same equilibrium distribution independent of the inlet distributions. Comparing the redistribution results in figure 5 with those in figures 2–4, it can be shown that the rate of mass and void exchange between the two subchannels as well as the final, or equilibrium, two-phase flow distributions were influenced by the mass flux. Decreasing the mass flux resulted in faster rate of mass and void exchange between the two subchannels, i.e. a shorter communication length was needed to achieve the equilibrium distribution and resulted in further stratification in that equilibrium distribution. The effect of mass flux was further discussed by Shoukri *et al.* (1982a).

2.4 *Discussion of the results*

In the absence of a transverse pressure difference between the two subchannels, the observed redistribution characteristics can be explained in terms of two mechanisms; gravity separation and turbulent mixing. Gravity separation tends to drive the gas upward

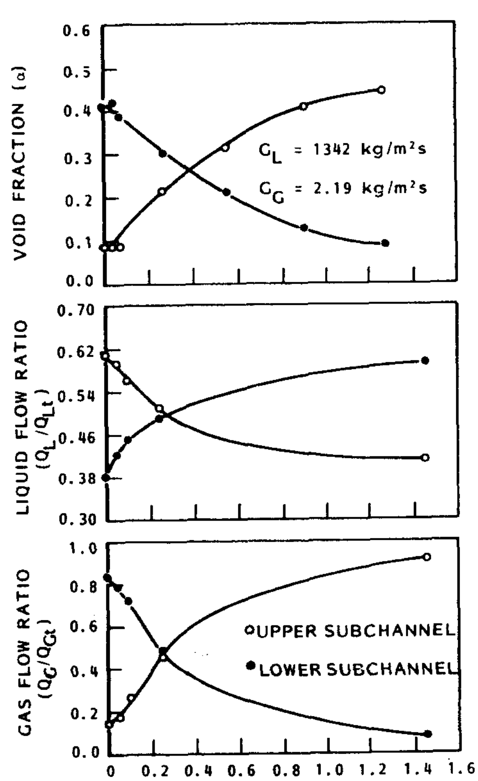

Figure 3. Redistribution results.

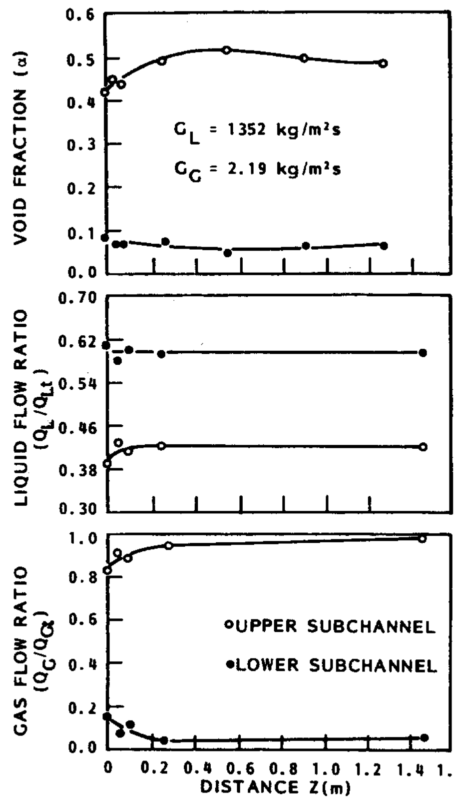

Figure 4. Redistribution results.

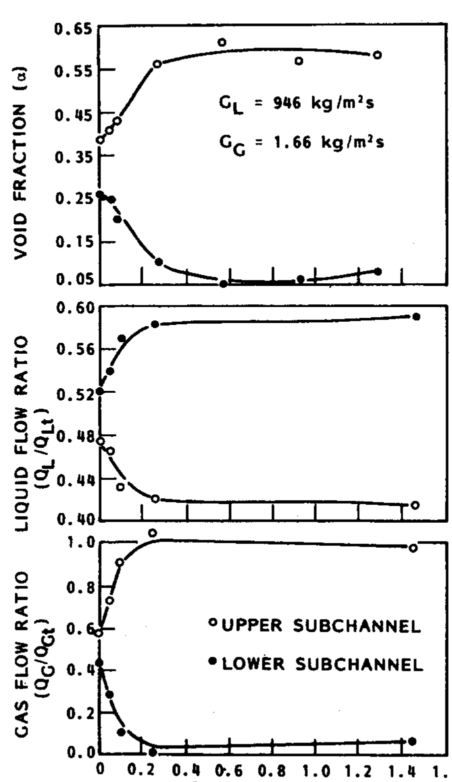

Figure 5. Redistribution results.

while the liquid is driven downward to fill the bottom subchannel. On the other hand, turbulent mixing tends to homogenize the flow distribution. For low mass flux, the effect of gravity separation prevails and the gas will tend to drift to the upper subchannel at a very high rate. Depending on the mass flux and the total gas flow rate, the bottom subchannel may be completely depleted of the gas. The effect of turbulent diffusion increases with increasing mass flux and its effect tends to oppose the gravity separation resulting in less stratification. For a higher mass flux, the turbulent diffusion mechanism becomes more significant and the rate of gas–liquid exchange becomes slower, as depicted from the redistribution curves. The turbulent diffusion mechanism is responsible for retaining some gas in the bottom subchannel against the gravity forces independent of the channel length.

The observed tendency of the flow to approach an equilibrium distribution beyond which no further exchange would take place can be explained in terms of these two mechanisms. The equilibrium distribution can actually be defined as the distribution for which the gravity separation effect is balanced by turbulent diffusion.

3. THE DEVELOPMENT OF A TRANSVERSE VAPOUR DRIFT MODEL

3.1 *Background*

In the development of a subchannel code for horizontal fuel channels, an appropriate constitutive relationship for the transverse vapour drift is needed. The needed relationship should include all the important parameters and be able to predict accurately the observed trends. Also, it should be compatible with the computer code it is to be used in conjunction with.

The basic formulation, in most subchannel codes, is based on the diffusion (or mixture) model. In the diffusion (or mixture) model, four field equations are used. These equations are: the mixture continuity, momentum and energy equations as well as the vapour continuity equation (the vapour is treated as the dispersed phase). Thus, the relative motion and energy difference should be expressed by additional constitutive equations. The constitutive relationship of interest herein is that required to express the relative motion of the two phases in the transverse direction.

Limited redistribution data were simulated by Shoukri *et al.* (1982b) as a diffusion process towards the measured equilibrium distributions from which a single redistribution parameter, encompassing both the gravity and turbulent diffusion effects, was determined. However, this simulation failed to express the distinction between the two components and required an independent evaluation of the equilibrium void distribution.

3.2 *The model*

In the analysis discussed in this section, the gas is the dispersed phase while the water is the continuous one. The model presented herein is based on the drift flux model as outlined by Zuber & Findlay (1965). The local vapour velocity V_G is related to the mxiture average volumetric flux density j through the local drift velocity V_{Gj}

$$V_G = \frac{j_G}{\alpha} = j + V_{Gj} \qquad [1]$$

where α is the void fraction and j_G is the gas volumetric flux density. The area average of a scaler or vector quantity F over the cross-sectional area A is given by

$$\langle F \rangle = \frac{1}{A}\int_A F\,\mathrm{d}A. \qquad [2]$$

By simple manipulation of [1], it can be shown that,

$$\frac{\langle j_G \rangle}{\langle \alpha \rangle} = C_0 \langle j \rangle + \bar{V}_{Gj}. \qquad [3]$$

The l.h.s. of [3] represents the void fraction weighted mean vapour velocity ($\langle \alpha V_{Gj} \rangle / \langle \alpha \rangle$) and $\langle j \rangle$ is the area average volumetric vapour flux density (superficial vapour velocity). C_0 is the distribution parameter ($C_0 = \langle \alpha j \rangle / \langle \alpha \rangle \langle j \rangle$) which accounts for the non-uniform distribution of α and j across the conduit. $\bar{V}_{Gj}$ is the void fraction weighted drift velocity ($\bar{V}_{Gj} = \langle \alpha V_{Gj} \rangle / \langle \alpha \rangle$). Ishii (1975) showed that the drift velocity can be expressed in terms of a local drift velocity and a diffusion term to account for void drift due to the concentration gradient. Accordingly, he proposed a linear kinematic constitutive relationship for $\bar{V}_{Gj}$ in the form,

$$\bar{V}_{Gj} = V_\infty - \frac{\epsilon_\alpha}{\alpha} \nabla \alpha \qquad [4]$$

in which ϵ_α is the turbulent void diffusion coefficient. The first term in the r.h.s. of [4] is the vapour rise velocity in a stagnant mixture V_∞ (local drift) which accounts for the gravity effect, while the second term is the void drift caused by the concentration gradient. Substituting [4] into [3], the mean gas velocity becomes

$$\frac{\langle j_G \rangle}{\langle \alpha \rangle} = C_0 \langle j \rangle + V_\infty - \frac{\epsilon_\alpha}{\alpha} \nabla \alpha. \qquad [5]$$

Applying [5] on two identical horizontal subchannels placed one above the other as shown in figure 6, the transverse gas volumetric flow rate through a gap spacing C and over an axial distance dz, in the absence of a transverse pressure difference, may be written as

$$dQ'_{G_{ij}} = (c \cdot dz) \cdot \langle j'_G \rangle$$

$$= c \cdot dz\bar{\alpha} \left\{ \langle j'_{ij} \rangle + V_\infty - \frac{\epsilon_\alpha}{\bar{\alpha}} \frac{(\alpha_j - \alpha_i)}{\Delta l} \right\} \qquad [6]$$

in which C_0 is unity in the transverse direction. Equation [5] is similar to an expression presented earlier by Rowe (1981). The transverse gas mass flux $G'_{G_{ij}}$ can then be written as

$$G'_{G_{ij}} = (\rho_G \bar{\alpha}) \left\{ \langle j'_{ij} \rangle + V_\infty - \frac{\epsilon_\alpha}{\bar{\alpha} \Delta l} (\alpha_j - \alpha_i) \right\} \qquad [7]$$

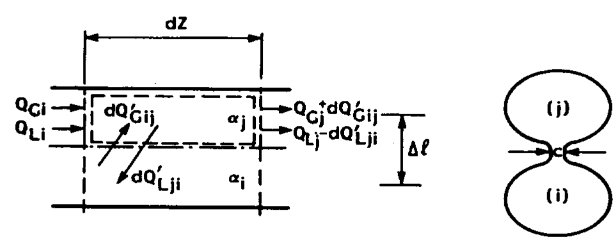

Figure 6. Gas–liquid exchange model.

where ρ_G is the gas density and j'_{ij} is the mixture transverse volumetric flux density. Expressions [6] and [7] indicate that the transverse vapour drift velocity varies along the communication length as the relative magnitude of the gravity separation term changes with respect to the turbulent void diffusion term until reaching the equilibrium distribution for which $G'_{G_{ij}} = 0$. Correlations for the terminal vapour velocity in a stagnant mixture V_∞ are available in the literature. A widely accepted correlation in the literature, as was shown by Ishii (1975) and Wallis (1974), is given by

$$V_\infty = A'\left[\frac{\sigma g(\rho_L - \rho_G)}{\rho_L^2}\right]^{1/4} \qquad [8]$$

where σ is the surface tension, ρ_L is the liquid density and the constant A' varies from 1.18 to 2.9. The advantage of this correlation, in the present analysis, is its independence of the bubble size.

When equilibrium distribution is reached, both $G'_{G_{ij}}$ and $\langle j'_{ij}\rangle$ approach zero and [7] reduces to

$$V_\infty = \frac{\epsilon_\alpha}{\bar{\alpha}\Delta l}(\alpha_j - \alpha_i)_{eq}. \qquad [9]$$

3.3 *Data reduction*

The initial objective was to use the data to estimate the values of the void diffusion coefficient and the coefficient A' of the gravity separation term[8]. Rearranging [7]

$$\frac{G'_{G_{ij}}}{\rho_G\bar{\alpha}} - \langle j'_{ij}\rangle = A'\left[\frac{\sigma g(\rho_L - \rho_G)}{\rho_L^2}\right]^{1/4} - \frac{\epsilon_\alpha}{\bar{\alpha}\Delta l}(\alpha_j - \alpha_i). \qquad [10]$$

By using the best fit of the redistribution curves, numerical values for the different parameters of [10] were obtained at different axial locations. Multiple linear regression was then used to obtain the best estimate for ϵ_α and for A' for each experimental run. It was found that the value of A' varies between 1.0 and 2.25 with no particular correlation with either the mass flux or the quality of the mixture. The average value for A' was found to be 1.4. This value agrees with the recommended coefficient for bubble rise velocity in turbulent churn flow (Ishii 1975). The same coefficient was recommended by Wallis (1974) for the region in which vapour rise velocity is independent of bubble size. Accordingly, the value of A' was fixed at 1.4 and the analysis was repeated to obtain the best estimate of the void turbulent diffusion coefficient ϵ_α.

3.4 *Turbulent mixing coefficient*

The calculated values of the void turbulent diffusion coefficients ϵ_α as a function of the average volumetric flux ratio for different mass fluxes are shown in figure 7. It is apparent that the void diffusion coefficient increases with increasing flow quality and mass flux. This is rather expected since the turbulence level increases with increasing mass flux and quality resulting in stronger mixing (diffusion) against the gravity separation effects.

The turbulent void diffusion coefficient ϵ_α is used to define a dimensionless turbulent mixing coefficient Ω,

$$\Omega = \epsilon_\alpha/Ud_h \qquad [11]$$

where d_h is the hydraulic diameter and U is the average flow velocity, i.e. $U = (Q_{Lt} + Q_{Gt})/A$, where Q_{Lt} and Q_{Gt} are the total volumetric flow rates of the liquid and

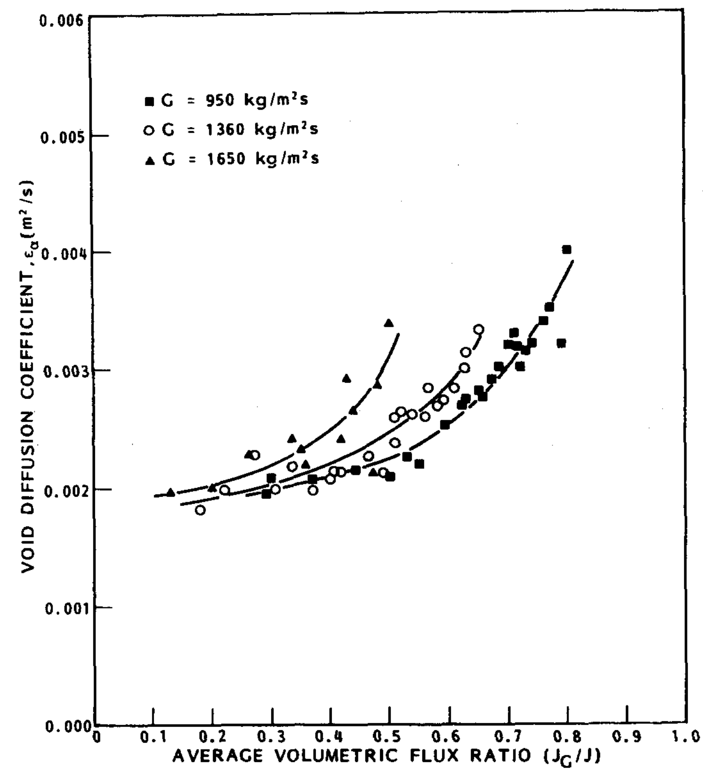

Figure 7. Void diffusion coefficients.

gas respectively. The calculated dimensionless turbulent mixing coefficients appear to be independent of the volumetric quality as depicted in figure 8. From the same figure, the mass flux seems to have some effect on the value of the mixing coefficient. Average values of 0.055, 0.06 and 0.068 appear to be appropriate for the mass fluxes of 950, 1360 and 1650 kg/m^2s, respectively. However, as the range of these values is very small, an average turbulent mixing coefficient of 0.06 is recommended for the present range of experimental data.

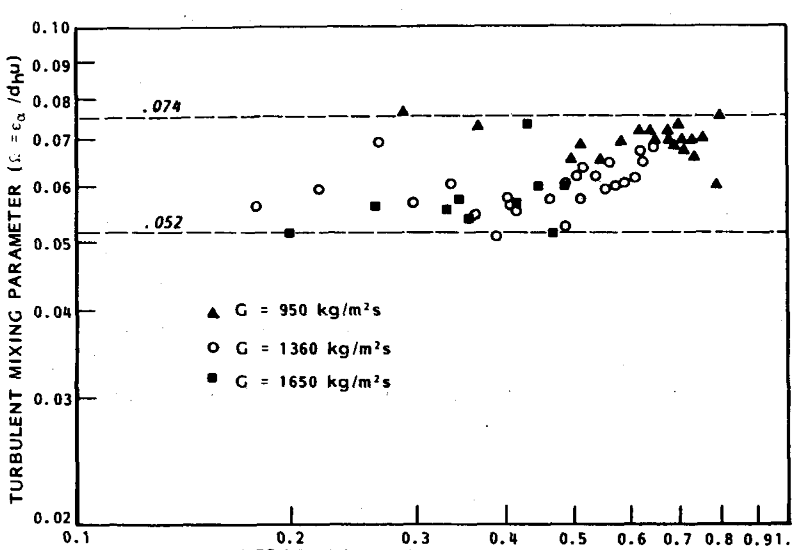

Figure 8. Turbulent mixing coefficients.

It is important to note that in determining the turbulent diffusion coefficients, [9] can also be used with the experimentally determined equilibrium void fraction difference $(\alpha_j - \alpha_i)_{eq}$. The resulting void diffusion coefficients were within 5% of that determined by the regression analysis for all runs. Also, it is interesting to note that the earlier model presented by Shoukri *et al.* (1982a) is basically similar to the one presented herein if [9] is used to predict the required equilibrium void fraction distribution.

4. CONCLUSIONS

—Extensive data on two-phase redistribution in two identical horizontal subchannels one placed above the other, in the absence of a transverse pressure gradient, was obtained. The measurements included the axial distribution of void fraction and liquid and gas flow rates in the two subchannels. The data could be useful in computer code verification and for the development of constitutive relationships needed to describe the interactions between adjacent horizontal subchannels.

—The observed redistribution results were explained in terms of two mechanisms; gravity separation and turbulent void diffusion. Gravity forces tend to cause phase separation while the turbulent void diffusion tends to homogenize the distribution of the two phases. The relative importance of each mechanism was found to be function of both mass flux and flow quality.

—The two-phase redistribution data exhibited an asymptotic behaviour approaching certain favoured (or equilibrium) flow distributions beyond which no further exchange was observed. The equilibrium distributions were found to be function of mass flux and volumetric flow quality but independent of the inlet flow distribution. Reaching an equilibrium distribution is caused by a balance between the two mechanisms of gravity separation and turbulent void diffusion.

—A constitutive relationship for the transverse vapour drift was presented. The vapour drift velocity consisted of two terms; one related to the bubble terminal velocity in a stagnant medium and the second to account for void drift due to the transverse void gradient, i.e. turbulent void diffusion. The experimental data were used to calculate the turbulent diffusion coefficient and it was found to increase with increasing mass flux and volumetric flow quality. A dimensionless mixing (turbulent diffusion) parameter was defined for which a constant value was recommended independent of the mass flux and flow quality.

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