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TWO-PHASE HYDRODYNAMIC EXPERIMENTS WITH AXIAL FLOW THROUGH SEVEN-ROD CLUSTERS

D. R. H. BEATTIE and K. R. LAWTHER
AAEC Research Establishment, Lucas Heights, NSW 2232, Australia

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Abstract—Hydrodynamic experiments have been carried out with upflow of air–water mixtures through vertical seven-rod clusters at atmospheric pressure. Results obtained from measurements of flow characteristics, including pressure drops, local velocity and voidage distribution, are discussed in terms of relations developed for two-phase flow in round tubes. Effects on the flow characteristics of spacer elements and bowing of a cluster are also discussed.

INTRODUCTION

An understanding of two-phase fluid mechanics in complex channel geometries is required because of the importance of flow boiling in water-cooled nuclear reactor systems, particularly in relation to predicting the consequences of accident or other abnormal conditions. At the Australian Atomic Energy Commission Research Establishment, single phase turbulent flow theory is being adapted to two-phase flows (Beattie 1972). Turbulence theory is not readily adaptable to flow in channels of complex geometry, even for single phase flow (Hooper 1975). However, it is known (e.g. Tong & Weisman 1970) that with single phase flow, pressure loss equations for flow in round tubes can be extended, with little loss in accuracy, to complex geometries by replacing the diameter term in relevant dimensionless groups with the equivalent hydraulic diameter, $D_e = 4\ A/p$, where A is the flow area and p is the sheared surface perimeter.

Although the use of D_e is based on empiricism rather than theory, it has led to reasonably accurate predictive methods for single phase flows in complex geometries. As a result, the AAEC program examined the validity of applying expressions obtained from mixing-length theory (as developed for two-phase flow through round tubes) to rod bundle geometries, by using the equivalent diameter concept (Beattie 1979). In that work, a large number of data from various sources were considered, with emphasis on high pressure steam–water systems, and the equivalent diameter concept was concluded to be valid for pressure loss and void fraction expressions. However, it was noted that the flow disturbance effects of the entrance region and of spacers in complex geometries may cause coefficients in the equations to be different from those for round tubes.

An investigation into the validity of the mixing-length concept for two-phase flows requires experimental data on such local flow structure as voidage and velocity profiles, as well as more global characteristics such as friction factors and average void fractions. Although in the literature there are several sources of data on such global and local characteristics of two-phase flow in round tubes, this is not the case for two-phase flow in complex geometries. Therefore, experiments have been conducted on seven-rod clusters for air–water flows in which local voidage and velocity data were obtained, as well as data on friction factors, average void fractions and rod-spacer pressure loss coefficients. The results of this investigation are reported here.

Air–water at atmospheric pressure is a convenient fluid system for two-phase flow experiments. Although the liquid/gas density ratio is much higher than the water/steam density ratio in a water-cooled nuclear power reactor under normal operating conditions, information obtained on flow characteristics from such experiments at low quality conditions would probably have general relevance to vapour/liquid systems and be particularly relevant to a water-cooled reactor system under the depressurisation conditions of a loss-of-coolant accident.

BACKGROUND THEORY

Relevant equations developed from the Prandtl mixing-length concept, as applied to two-phase flows in round tubes, are presented below Detailed discussion of these equations has been presented elsewhere (Beattie 1972, 1976, 1977).

Pressure drop components

The acceleration component of the axial gradient in static pressure is negligible in air–water upflow experiments of the type described here. Effectively the pressure gradient, $\mathrm{d}P/\mathrm{d}z$, is made up of two components, i.e.

$$\mathrm{d}P/\mathrm{d}z = [\mathrm{d}P/\mathrm{d}z]_f + [\mathrm{d}P/\mathrm{d}z]_g \qquad [1]$$

where $[\mathrm{d}P/\mathrm{d}z]_f$ is the frictional component given by

$$[\mathrm{d}P/\mathrm{d}z]_f = 2f\,G\langle j\rangle/D_e, \qquad [2]$$

and $[\mathrm{d}P/\mathrm{d}z]_g$ is the gravitational component, given by

$$[\mathrm{d}P/\mathrm{d}z]_g = \{\rho_L(1-\langle\alpha\rangle) + \rho_G\langle\alpha\rangle\}g\,. \qquad [3]$$

In the above, f is the friction factor, G is mass flux of fluid mixture, $\langle --- \rangle$ denotes a cross-section average value, j is mixture velocity, α is void fraction, ρ_L and ρ_G are the densities of the liquid and gas phases, and g is the acceleration due to gravity.

The calculation of $\mathrm{d}P/\mathrm{d}z$ for a given flow thus depends on the values of friction factor, f, and void fraction, $\langle\alpha\rangle$. The methods adopted for evaluating these are described below.

Friction factor

The friction factor f, is dependent on the "friction regime" of the sublayer. Regimes are characterised by a triad (m, n, z) where m and n are integers which depend on the turbulent core flow structure and z is a letter (a, b or c here) indicating the nature of the sublayer (table 1). Relations between the friction factor and Reynolds number, $\mathrm{Re} = D_eG/\mu$, where the definition of the viscosity, μ, is sublayer-dependent (see table 1), are established through values of m and n by the equation (Beattie 1977):

$$1/\sqrt{f} = (\sqrt{2})^{m+4}\{\log \mathrm{Re}\sqrt{f} - (0.11m + 0.50n + 1.1)\}. \qquad [4]$$

An extensive analysis of data, some of which have been reported by Beattie (1977), indicated that, in the absence of strong flow-disturbing influences, the two lowest quality regimes are usually characterised by $(m, n, z) = (0, -2, a)$ (low-voidage bubble-sublayer flows) and (m, n, c) (semi-annular flows), where m and n for the semi-annular regime appear to depend on pressure and characteristic channel dimension. The boundary between these two regimes is given by:

$$f(0, -2, a) = f(m, n, c), \qquad [5]$$

Table 1. Two-phase flow sublayer viscosity relations

Sublayer type	*Viscosity relation*
(a) Rigid surface bubbles	$\mu = \mu_L(1 + 2.5\,\beta)$
(b) Non-rigid surface bubbles	$\mu = \mu_L\left\{1 + \left(\frac{\mu_L + 2.5\,\mu_G}{\mu_L + \mu_G}\right)\beta\right\}$
(c) Wavy gas–liquid interface	$\mu = \mu_L(1-\beta) + \mu_G\beta$

and the relation

$$f = \min\{f(0, -2, a), f(m, n, c)\} \quad [6]$$

selects the appropriate friction factor value.

In the case of obstructions, the relation between the two-phase pressure loss coefficient and Reynolds number coincides with the single phase relation if the Reynolds number, based on the relevant viscosity as given in table 1, is defined according to the nature of the flow over the obstruction (Beattie 1973).

Average voidage

Local voidage, α, and local velocity, j, vary with distance from the wall, y, such that

$$(1-\alpha)^{3/2} = a + b \ln y \quad [7]$$

and

$$j = a' + b' \ln y \quad [8]$$

where a, b, a', b' are coefficients which are independent of radial position (Beattie 1972).

For low-voidage distributed flows, the void fraction averaged over the cross-section, $\langle\alpha\rangle$, is given by the Zuber & Findlay (1965) equation:

$$\frac{\langle j_G\rangle}{\langle\alpha\rangle} = C_0\langle j\rangle + V \quad [9]$$

where $\langle j_G\rangle$ is the superficial gas velocity; $\langle j\rangle$ is the average mixture velocity; V is a regime-dependent drift velocity, values of which can be obtained from semi-empirical equations given by Zuber & Findlay (1965) and by Griffith (1964); and C_0 is a "distribution parameter" which accounts for the fact that the gas phase concentrates in the faster moving regions of the flow. The distribution parameter is regime-dependent and its value is given by Beattie (1977) as

$$C_0 = 1 + 2.60\,(\sqrt{2})^m\,\sqrt{(f(m, n, z))}. \quad [10]$$

For annular flow within no entrainment the liquid volume fraction, $1-\langle\alpha\rangle$, is related to the liquid volume flow fraction, $1-\beta$, by

$$Q^+ = \int_0^{S^+} j^+\,\mathrm{d}y^+ \quad [11]$$

where

$$Q^+ = \frac{1-\beta}{4}\,\mathrm{Re}\,(z), \quad [12]$$

$$S^+ = \frac{1-\langle\alpha\rangle}{4}\,\mathrm{Re}(z)\,\sqrt{\left(\frac{f(m, n, z)}{2}\right)}, \quad [13]$$

$\mathrm{Re}(z)$ is the Reynolds number for the relevant sublayer as given in table 1, and j^+ is the non-dimensional local velocity appropriate to the relevant (m, n, z) regime (Beattie 1977), expressed as a function of non-dimensional distance from the wall, y^+.

Interpretation of pressure drop data

Pressure gradients in experiments of the type described here may be dominated by the frictional component or by the gravitational component, or may have contributions of a similar magnitude from both these components. In the first two cases the pressure drop data may be used directly to estimate values of the friction factor or voidage respectively.

In cases where neither the frictional component nor the gravitational component dominates, conventional wisdom dictates that some additional measurement be made before the axial gradient of static pressure can be resolved into its two components. This is really unnecessary since the interrelation between void fraction and friction factor, as described above, provides a relation equivalent to that which would be obtained by the additional measurement.

Therefore, in principle, pressure gradient data covering a wide range of flow conditions for a particular flow regime can be used to determine the appropriate values of the triad (m, n, z) for that regime, and hence the values of both the frictional and gravitational components for a given flow condition, irrespective of the relative contribution of each to the total pressure gradient. In practice, however, the relatively weak dependence of distribution parameter on friction factor in [10] means that, for distributed flows, voidage data (or equivalently, gravity-dominated pressure gradient data) analysed in terms of [9] cannot provide accurate estimates of friction factors; so evaluation of (m, n, z) for the regime becomes uncertain. Examination of [11]–[13] reveals that the same problem arises with gravity-dominated pressure gradient data for annular flows. The uncertainty should disappear for pressure gradient data where the friction contribution becomes substantial.

EXPERIMENTAL PROGRAM

Experimental assemblies

Three different rod-cluster arrangements were used with upflow of air–water mixtures through vertical seven-rod clusters in a transparent shroud, 95 mm dia., 3.66 m length. Pressure tappings were located 1.97 and 2.69 m from the inlet end of the shroud.

The *first* cluster arrangement (42 mm equivalent dia. × 3.66 m) comprised a central rod, 15.9 mm dia., surrounded by six equidistant rods, 12.7 mm dia. on a pitch circle, 50.8 mm dia. The rods were held in position relative to each other by seven sets of spacers, made from 13 × 0.9 mm metal strip, which were placed at equal intervals along the cluster as shown in Figure 1. The cluster was held centrally in the shroud by connections screwed axially into the central rod at each end. A probe housing 2.07 m from the inlet end enabled local voidage and gas bubble velocity to be measured by a double-needle conductivity probe of the type commonly used in two-phase flow experiments (e.g. Herringe & Davis 1974). The probe could be moved in both radial and circumferential directions relative to the cluster.

The *second* cluster arrangement was the same as the first except that the rod bundle was bowed into near contact with the shroud, 2.44 m from the inlet end, by means of screwed rods through the shroud. The rod cluster was thus in an extremely eccentric position in the region of the pressure tappings and the double-needle probe.

The *third* cluster arrangement (17 mm equivalent dia. × 3.66 m) comprised seven 25.4 mm dia. rods in the same shroud, six rods being equispaced on a 60 mm pitch circle diameter around the seventh. Sets of spacers, each consisting of eighteen 4.7 mm lengths of 4.7 mm dia. threaded rod, separated the rods from each other and from the shroud, as shown in figure 1; one of these was located 1 m below the upstream pressure tapping and another 77 mm above the downstream tapping. Results from the first and second cluster arrangements indicated that spacers significantly influenced the flow, so for this assembly, in order to examine pressure recovery after the spacer, four additional pressure tappings were located downstream of the second spacer set as shown in figure 1. Voidage and velocity contour maps were not obtained with this cluster because of practical limitations associated with the small flow section.

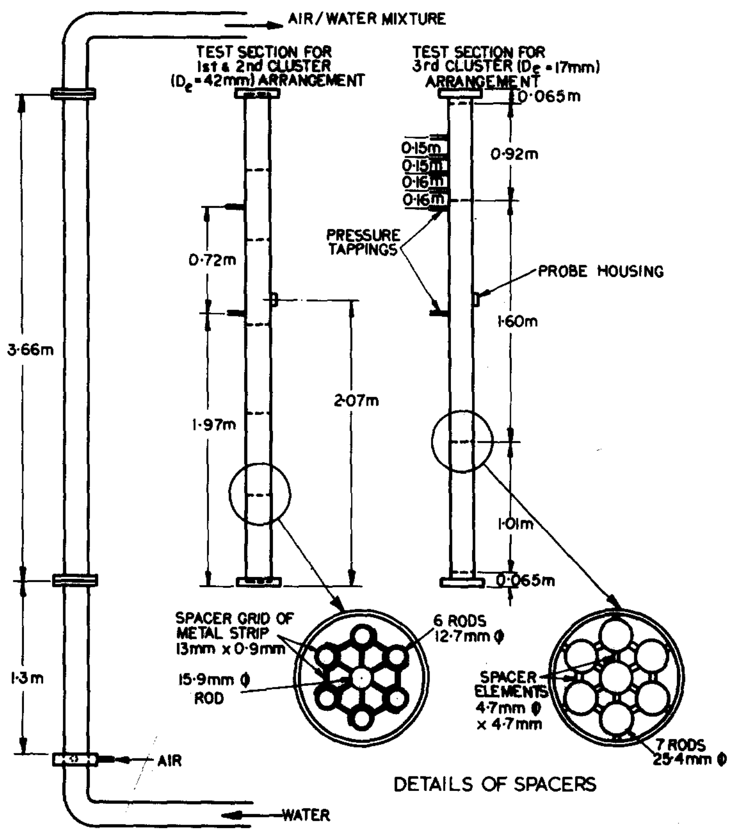

Figure 1. Test arrangements.

Experiment conditions

Experimental data were obtained for flows of air–water mixtures with atmospheric pressure at the test section exit. The flowrates for experiments with the first two cluster arrangements correspond to gas and liquid superficial velocities ranging from 0 to 3.0 m s^{-1} for $\langle j_G \rangle$, and 0 to 2.0 m s^{-1} for $\langle i_L \rangle$. Flowrates in the third cluster arrangement correspond to gas and liquid superficial velocities ranging from 0 to 16 m s^{-1} for $\langle j_G \rangle$, and 0.08 to 2.0 m s^{-1} for $\langle j_L \rangle$.

Gas and liquid flowrates were measured separately upstream of the mixer section. For the first two cluster arrangements, local phase content and gas bubble velocity data were obtained from radial traverses at the probe housing for a number of azimuthal positions of the probe housing, relative to the cluster.

RESULTS

(a) 42 *mm equivalent diameter, cluster arrangements*

(i) *Pressure gradient data.* Single phase pressure drop measurements resulted in friction factors for the first and second cluster arrangements which are respectively ~30 and ~20 per cent above those corresponding to the Nikuradse equation:

$$1/\sqrt{f} = 4 \log \mathrm{Re}\sqrt{f} - 0.4. \qquad [14]$$

These are somewhat higher than expected, and apparently reflect an influence of the spacers and the probe assembly. Further evidence of this influence comes from an analysis of the two-phase voidage data discussed below. The reduction of friction factors on bowing was expected and can be explained by a decrease in effective shear surface under bowed conditions.

The two-phase flows were observed to be bubble flows, either with or without slugs. Axial pressure gradients in these flows had significant contributions from both gravity and friction for the bubble-slug flows, whereas those in the bubble flows were due predominantly to gravity.

Pressure gradient data were analysed by subtracting estimates of the frictional component and, from the resulting gravitational components, average voidage values were obtained by means of [3], which were then plotted on the $(\langle j_G\rangle/\langle\alpha\rangle):\langle j\rangle$ plane.

The friction regime which, on the basis of round tube data for similar flow conditions, was expected to apply here, is that characterised by (0, −2, a) (Beattie 1977). However, $(m, n) = (0, -2)$ in [4] corresponds to the Nikuradse equation which, although valid for flow through round tubes, underpredicts the single phase friction losses for these assemblies; so values of two-phase friction factor used for estimating the frictional components were obtained for sublayer *a* (table 1) but based on the friction factor/Reynolds number relation corresponding to the experimental single phase values instead of the Nikuradse equation.

The resulting void fraction data are shown in figure 2. This figure shows that two distinct characteristics occurred, and that bowing did not have any detectable influence on the voidage characteristics. This latter finding is as expected since, as already noted, bowing has a small effect on the friction factor, and [9] and [10] indicate that, for a given regime, a change in friction factor has only a second-order effect on void fraction.

The boundary between the two characteristics on figure 2 occurs at a voidage of ~23 per cent. At lower voidage values the flow was visually observed to be bubble flow, and at higher voidages, bubble-slug flow.

The bubble flow data have drift velocity values which are negative and approximated by $V = -\langle j_L\rangle$, and distribution parameters C_0 which are large (~2.0) and, in view of [10], are incompatible with the *a* type sublayer regime, for which $C_0 \sim 1.2$. This indicates that the estimated frictional components for these data are incorrect. However, as noted, the frictional components for these data are negligible; hence the void fraction values for these data would not be invalidated.

The negative drift velocities and the incompatibility of the distribution parameter values with the *a* type sublayer regime, indicate that the flow was strongly underdeveloped. As air

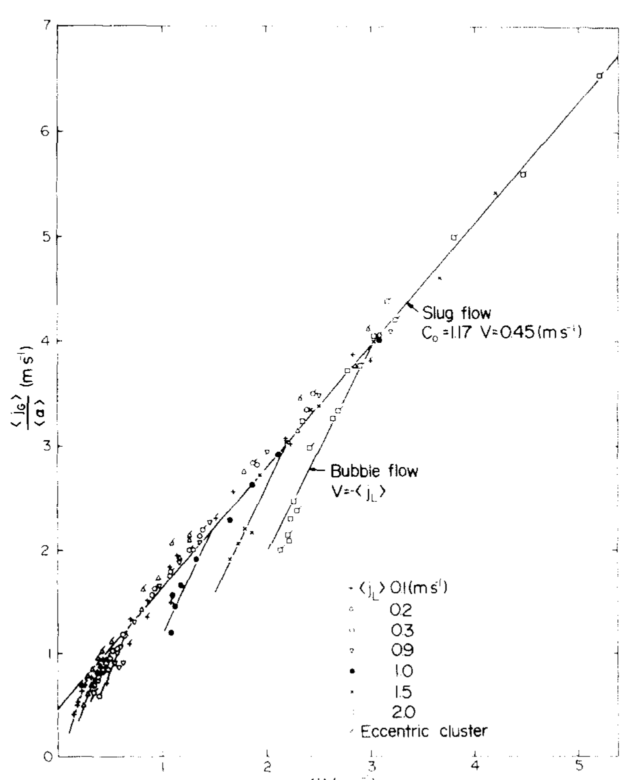

Figure 2. Average voidage data for bowed and non-bowed 42 mm equivalent dia., rod cluster.

"wakes" were observed at the spacers, the flows could have been disturbed by a bubble-retarding action of the spacers which would have produced a drift velocity of $-\langle j_L \rangle$ and also prevented establishment of the (0, −2, a) regime.

The slug flow data of figure 2 are very close to a slug flow version of [9], in which values of $C_0 = 1.17$ and $V = 0.45\ \mathrm{m\,s^{-1}}$ were obtained from curves given by Griffith (1964).

The agreement with the Griffith equation appears encouraging but, given his computational procedure (zero net flow experiments to obtain V, and speculative arguments to derive C_0 values), it seems rather surprising. Close examination of the slug flow data, however, reveals a small but significant mass flux effect. Figure 3 indicates that although the Griffith equation is in fair agreement with the data, the actual drift velocity, V, is somewhat lower than that proposed by Griffith, and C_0 values are really mass-flux dependent and larger than that recommended by Griffith.

Figure 3 also indicates that distribution parameter values are compatible with [10] for the $(0, -2, a)$ friction regime, thus confirming the method of obtaining the frictional component of the pressure drop, which was not negligible for the bubble-slug flow.

(ii) *Flow structure.* The double-needle conductivity probe was used to obtain local voidage and bubble velocity contour maps for selected flow conditions in both cluster arrangements. The conductivity probe measurements were confined to bubble flows because preliminary tests indicated that meaningful velocities could not be obtained if slugs were present.

Figures 4 and 5 show typical flow structure results in which the velocity and voidage contours follow the broadly expected trends, but two points are noteworthy. The first is that the rods are not necessarily at the centre of the subchannel boundaries obtained from the contours; this is relevant for rod-centred subchannel analysis studies. The second point is that secondary flows, as evidenced by irregularities in the velocity contours in the rod-free region of the bowed cluster data, play a stronger role than is the case in single phase flows. A similar situation occurs in two-phase flows around bends (Hoang & Davis 1977).

The two-phase mixing-length theory expressions for bubble flow, [7] and [8], appear to be locally valid (figures 6 and 7), although, as is the case in single phase flow through rod-cluster assemblies (Hooper 1975), for any given flow, values of the coefficients vary with azimuthal

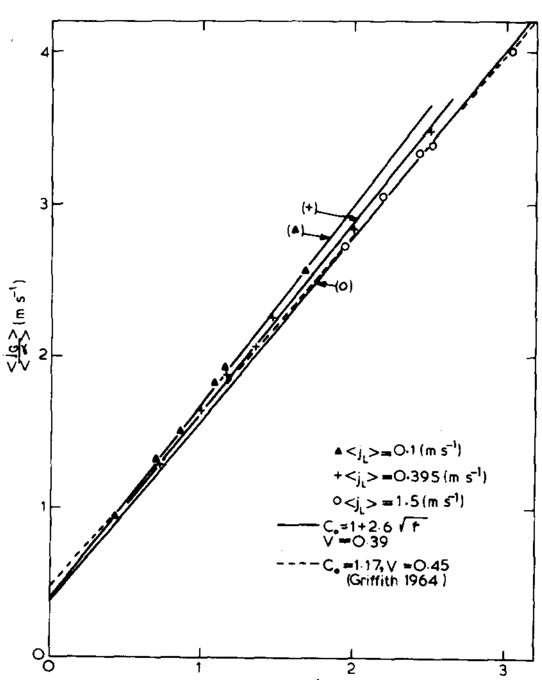

Figure 3. The effect of mass flux on slug flow void fraction (42 mm equivalent dia., non-bowed rod cluster).

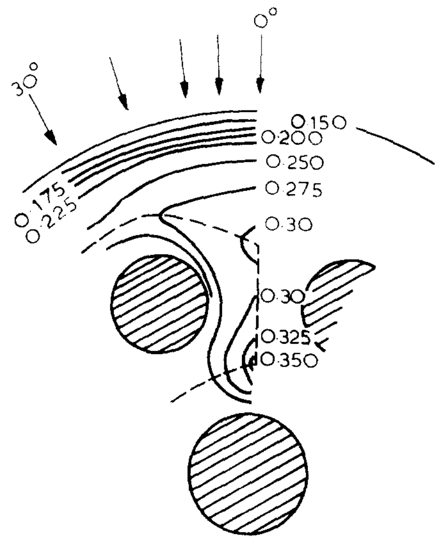

Figure 4. Voidage contour map for non-bowed 42 mm equivalent dia., rod cluster with $\langle j_L \rangle = 0.390\ \mathrm{m\,s^{-1}}$ and $\langle j_G \rangle = 0.175\ \mathrm{m\,s^{-1}}$. Probe traverse positions are arrowed.

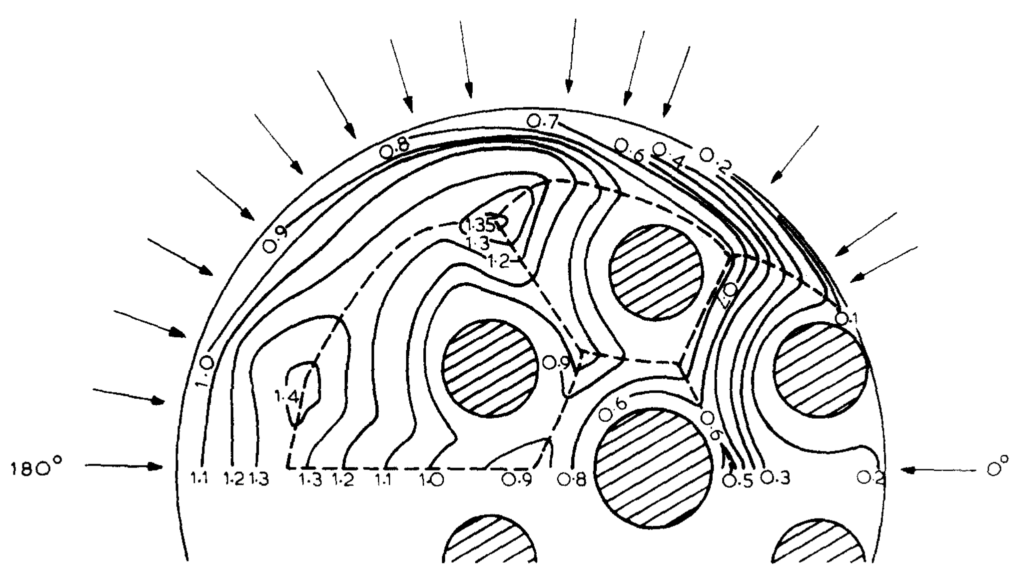

Figure 5. Bubble velocity contour map in $\mathrm{m\,s^{-1}}$ for bowed 42 mm equivalent dia., rod cluster with $\langle j_L \rangle = 0.320\ \mathrm{m\,s^{-1}}$ and $\langle j_G \rangle = 0.175\ \mathrm{m\,s^{-1}}$. Probe traverse positions are arrowed.

position. The steep velocity profiles are consistent with the large distribution parameter values found in the average voidage analysis, although no quantifiable crosscheck between the two quantities can be made at present.

(b) 17 *mm equivalent diameter, cluster arrangement*

(i) *Pressure losses.* Pressure gradients were examined upstream and downstream of one of the spacers. For superficial liquid velocities greater than $1\ \mathrm{m\,s^{-1}}$, the pressure gradient was predominantly frictional, and the gravitational component was allowed for, using [9] with the bubble flow expression for drift velocity (Zuber & Findlay 1965)

$$V = 1.4\,(\sigma g/\rho_L)^{0.25} \qquad [15]$$

where σ is the surface tension; and distribution parameter, C_0, equal to 1.2, this being an

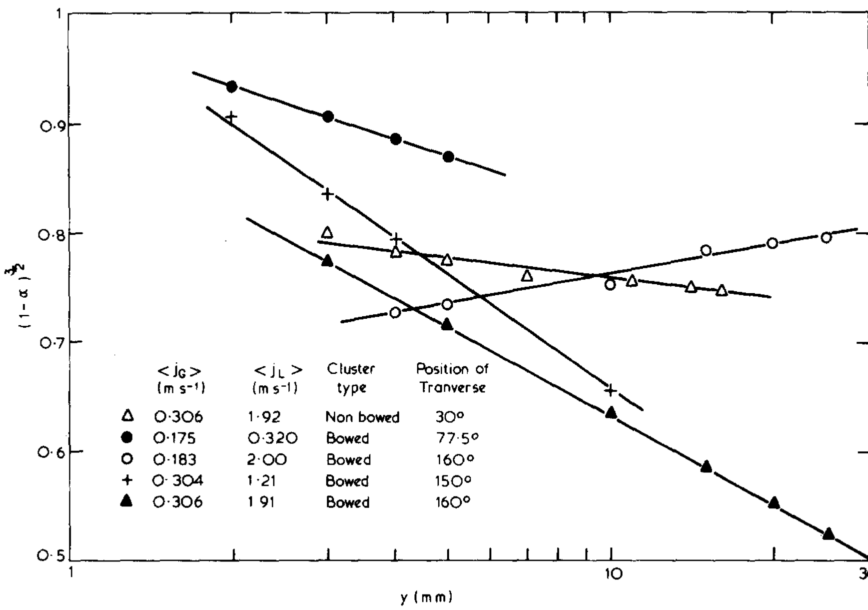

Figure 6. Voidage distribution data near shroud of 42 mm equivalent dia., rod cluster.

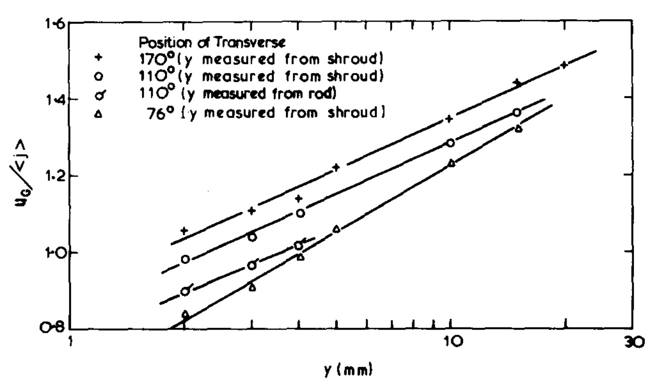

Figure 7. Velocity distribution data near the wall for 42 mm equivalent dia., rod cluster with $\langle j_L \rangle = 2.00\ \mathrm{m\,s^{-1}}$ and $\langle j_G \rangle = 0.18\ \mathrm{m\,s^{-1}}$.

approximation to values calculated from [10] for the $(0, -2, a)$ friction regime anticipated for these flow conditions (Beattie 1977). Errors in this voidage calculation procedure have a negligible effect on the estimate of the frictional component for superficial liquid velocities greater than $1\ \mathrm{m\,s^{-1}}$.

The pressure gradients downstream of the spacer, determined from measurements at the four downstream pressure tappings, indicated that the effect of the spacer had largely disappeared after five hydraulic diameters and rarely extended to 15 diameters. Friction factors beyond 15 diameters downstream of the spacer were the same as those upstream of the spacer. The upstream and the recovered downstream axial static pressure profiles were extrapolated to determine the pressure losses associated with the spacer, and hence the spacer loss coefficients.

Low voidage, pressure loss data were consistent with sublayer type a (table 1), and pressure losses at higher voidages, with sublayer type c. The lower voidage friction factors are shown in figure 8 and generally correspond to $f(0, -2, a)$ as obtained from [4] (which gives the Nikuradse equation). As shown in figure 8, single phase data also are consistent with the same curve. The applicability of $f(0, -2, a)$ verifies the method used to estimate the gravitational components in the pressure gradient data, and indicates that spacer effects are smaller for this

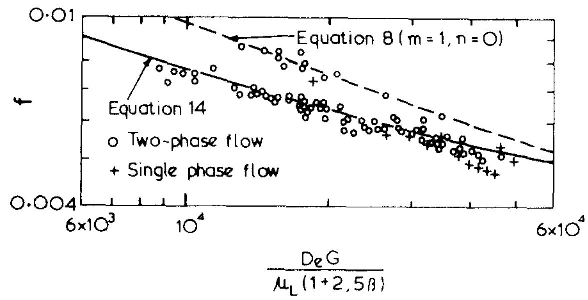

Figure 8. Bubble flow friction factors upstream of spacer of 17 mm equivalent dia., rod cluster.

cluster than the previous one. This is consistent with the rapid pressure recovery following the spacer as noted above. A few of the data in figure 8 deviate from $f(0, -2, a)$ and instead, were correlated by $f(1, 0, a)$.

The friction data for higher voidages could not be correlated with [4] if m and n are integers. However, the data do agree with the equation if a half-integer value of m is used. It has been noted elsewhere (Beattie 1977) that, although [4] is compatible with most data sets by appropriate integer choice for m and n, some data require half-integer values. As shown in figure 9, the higher voidage friction data for cluster arrangement No. 3 are consistent with $f(-2, -6.5, c)$.

In line with the general case described by [6], all friction factor values for $\langle j_L \rangle$ above 1 m s^{-1} in this cluster agree with

$$f = \min \{f(0, -2, a); f(-2, -6.5, c)\}. \qquad [16]$$

It has been suggested (Beattie 1973) that single phase pressure loss coefficient/Reynolds number curves should apply to the two-phase case, provided that the two-phase Reynolds number is appropriately defined. This is the case with the present spacer loss coefficient data (figure 10). The applicability of Reynolds number, based on sublayer c for all the data, indicates that flow over the spacers was separated flow for both low and high voidage conditions. The scatter in the data is caused by the relatively small pressure drop across the spacer, combined with the extrapolation procedure necessary to estimate this pressure drop.

For superficial liquid velocities less than 1 m s^{-1}, the pressure drop was predominantly gravitational. However, the frictional component was not negligible, particularly at high voidages. Being predominantly gravitational, these data more appropriately belong in the next section. The analysis discussed there indicates that the friction factors at low voidage do not agree with $f(0, -2, a)$ and instead agree with $f(4, -1, a)$ which indicates an undeveloped flow condition at low superficial velocities.

(ii) *Void fraction*. As already stated, the pressure gradient data were gravity-dominated at superficial velocities less than 1 m s^{-1}. For larger liquid velocities, friction factors were calculated by assuming that voidage could be evaluated from [9] using the estimate based on $f(0, -2, a)$, for distribution parameter in [10] and the drift velocity for bubble flow in [15]. This led to friction factor values compatible with $f(0, -2, a)$, at least for low voidages, suggesting that, for these data, the procedure for calculating voidage was correct. On the other hand, friction factors for flows with higher voidage, $f(-2, -6.5, c)$, indicate that the procedure used for calculating voidage is not correct at higher voidages. Since, for these conditions, the gravity component in the pressure gradient was negligible, voidage data cannot be extracted from these data. However, voidage values calculated for the $(-2, -6.5, c)$ regime, using relationships given in the section on background theory, should apply to these data.

Although pressure gradient data were gravity-dominated at low superficial liquid velocities ($<1 \text{ m s}^{-1}$), the frictional components were not negligible and needed fairly accurate estimation. Lower voidage values for these liquid flowrates were initially assessed by assuming that

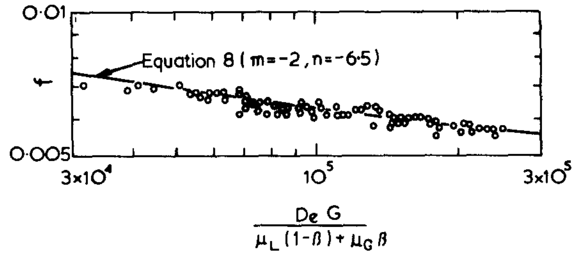

Figure 9. Annular flow friction factors upstream of spacer of 17 mm equivalent dia., rod cluster.

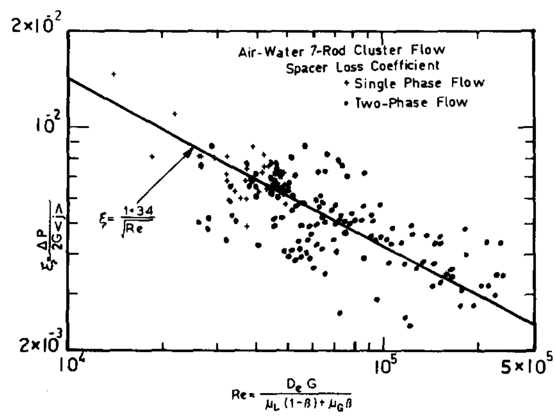

Figure 10. Spacer loss coefficients for 17 mm equivalent dia., rod cluster.

$f(0, -2, a)$ applies for the frictional component. However, this assumption led to estimated values of voidage which were incompatible with the $(0, -2, a)$ regime. Trial and error indicated that, if friction was calculated according to $f(4, -1, a)$, the resulting estimates of voidage, when plotted on the $\langle j_G \rangle / \langle \alpha \rangle$: $\langle j \rangle$ plane, produced distribution parameters from [10] consistent with $f(4, -1, a)$, indicating that $(4, -1, \mathrm{a})$ is the appropriate regime for these conditions. The void fraction data so estimated are shown in figure 11. Note that the two empirical drift velocity values from figure 11 agree with the bubble flow drift velocity, 23 cm s^{-1} given by [15], and the drift velocity for developed slugflow in rod clusters, calculated from the graphs of Griffith (1964).

It would appear from the above that, for the 17 mm rod cluster, spacers did not influence the flow at high mass-flux bubble flows, but at low mass-flux bubble flows the regime was altered from $(0, -2, \mathrm{a})$ to $(4, -1, \mathrm{a})$. However, unlike the case with the 42 mm cluster, drift velocity values were not noticeably affected.

In the case of annular flows at low mass flux (i.e. $\langle j_L \rangle < 1$ m s^{-1}), various frictional relations were tried for the frictional component of the pressure drop, but none corresponded to voidage values compatible with the original friction factor assumptions. However, an assumed friction factor of 0.006, which is reasonable in view of the annular flow friction factor data of figure 9, resulted in voidage values which, when analysed in the annular flow plane

$$\left\{\frac{1-\beta}{4}\mathrm{Re}\right\} : \left\{\frac{1-\langle\alpha\rangle}{4}\mathrm{Re}\sqrt{\left(\frac{f}{2}\right)}\right\},$$

were well correlated, provided that Re was defined using viscosity a (figure 12). No spacer effect is discernible. Furthermore, the correlating equation is the integral of the "universal" velocity profile. Thus, although the flow cannot be specified completely, the conclusion can be drawn that the data of figure 12 are for annular flow with entrained bubbles in the film, with the

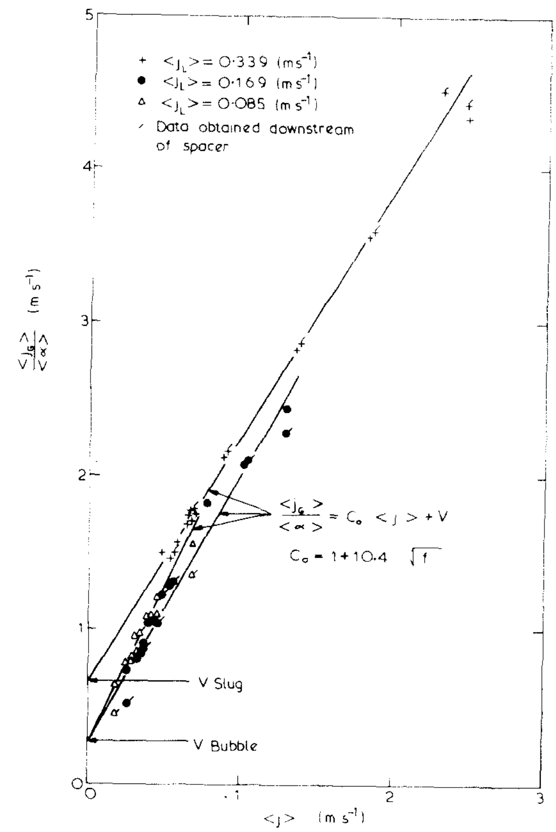

Figure 11. Bubble flow voidage data for 17 mm equivalent dia., rod cluster.

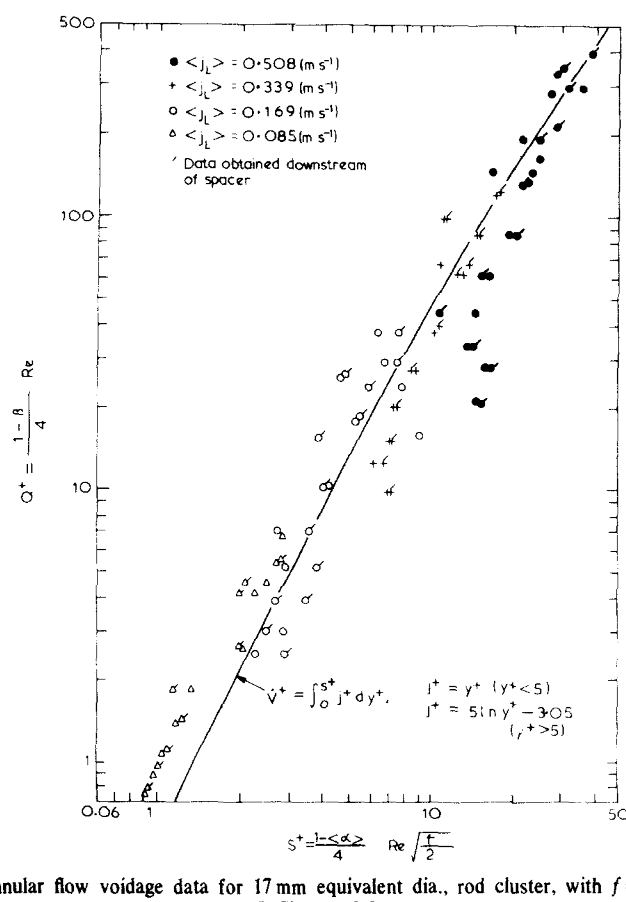

Figure 12. Annular flow voidage data for 17 mm equivalent dia., rod cluster, with $f = 0.006$ and Re $D_eG/\mu_L(1 + 2.5\,\beta)$.

"universal" velocity profile being valid within the film, but that deviations from the "universal" profile occur in the core region, such that $f \sim 0.006$ for the flow conditions of figure 12.

COMPARISONS WITH OTHER TWO-PHASE FLOW ROD CLUSTER DATA

Data on average void fraction from relatively low pressure systems (Condon & Sher 1962, Muchiyoshi & Serizawa 1970, Moussez *et al.* 1965) have characteristics similar to those obtained here, with strong mass-flux effects and negative drift-velocities at low voidages, and at high voidages have constant drift-velocities and distribution parameters consistent with [10] ($m = 0$). The results from Moussez *et al.* (1965) are particularly interesting: as in the case here, a test section modification (the introduction of swirlers rather than the bowing used in this work) produced changes in friction characteristics but no discernible changes in average voidage characteristics. However, with at least one exception (Sher *et al.* 1965), which behaves as above, high pressure steam–water distributed flow data for average void fraction (Agostini *et al.* 1971, Schoneberg 1968, Nylund *et al.* 1967–70) behave differently, corresponding to developed bubble-flow behaviour, with C_0 given by [10] (m = 0) and drift velocity by [15]. High pressure, low voidage, two-component flows (Alia *et al.* 1968*a*, *b*, Colombo *et al.* 1967) have values of the distribution parameter which also are consistent with [10] (m = 0).

Only limited data are available in the literature on two-phase flow structure in rod bundles. Low voidage, local void fraction and velocity data for diabatic steam–water flow in a seven-rod cluster (Bosio & Imset 1973) have similar trends to the data presented here. Detailed data have been reported by Schraub *et al.* (1969) for annular air–water flow in a nine-rod cluster. As with the present experiments, the shroud surface appears to influence the flow more strongly than the rod surfaces. Rod-cluster voidage profiles obtained from radiation attenuation methods (Condon & Sher 1962, Sher *et al.* 1965, Nylund *et al.* 1967–70) are necessarily only semi-local, and cannot be readily compared with the present data. Nevertheless, it is of interest that such local voidage data (Sher *et al.* 1965), both near rods and near the shroud, are consistent with [7].

Friction factor data for low voidage flows through rod clusters generally correspond to the (0, −2, a) friction regime (Beattie 1979) as found here. However, several exceptions have been noted (Beattie 1979), and it is interesting that some data from the 17 mm equivalent dia., cluster arrangement are consistent with $f(1, 0, a)$ since low quality steam–water data which deviate from $f(0, -2, a)$ often agree with $f(1, 0, a)$: for example, data from the 3.64 mm annulus used by Tarasova *et al.* (1966) and Klyushnev & Tarasova (1966) appear to have a substantial amount of scatter, but this is because some are consistent with $f(1, 0, a)$ and the rest with $f(0, -2, a)$; also, all the data for annulus 140 A of Adorni *et al.* (1965) provide another example. With regard to the $f(1, 0, a)$ data of figure 8, there were no obvious differences in operating conditions for these data. In fact, some points represent non-repeatability for nominally identical conditions.

In general, friction data for high voidage flows through rod clusters have been found to depend on surface tension rather than viscosity, in a friction factor/Weber number relation which depends on a number of duct geometry factors, including details of the rod spacers (Beattie 1979). However, this is not the case here where $f(0, -2, a)$ applies for the 42 mm cluster and $f(-2, -6.5, c)$ for the 17 mm cluster.

CONCLUSIONS

Experiments with air–water flows through seven-rod clusters have provided data on local velocity and voidage distribution, friction factors and average voidage. These data are consistent with a mixing-length concept developed for two-phase flow in round tubes and applied to rod cluster assemblies by using the equivalent diameter concept.

Bowing of a rod cluster resulted in a decrease of ~ 10 per cent in two-phase friction loss, even though secondary flows appear to play a stronger role in two-phase flows than in single phase flow. There was no discernible effect on average voidage.

The presence of rod spacer grids can result in flow characteristics consistent with non-developed flow conditions. Single phase pressure loss coefficients of rod spacer elements are applicable to two-phase flow conditions for the appropriate Reynolds numbers.

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