

## BRIEF COMMUNICATION

### THE EFFECT OF VARYING GAS VOIDAGE DISTRIBUTIONS ON AVERAGE HOLDUP IN VERTICAL BUBBLE FLOW

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#### INTRODUCTION

Although current two-phase flow research is concerned with the measurement of local flow properties, most engineers will still employ models requiring only average quantities in a design. The Zuber & Findlay (1964) drift-flux model is used to predict gas holdup in vertical bubble flow, but the literature disagrees as to whether the profile constant,  $C_0$ , is invariant with respect to gas and liquid superficial velocities. Data for air-water bubble upflow in a 100mm pipe has revealed some variation in  $C_0$ , so that a more accurate holdup model must be sought.

#### THE DRIFT-FLUX MODEL

The drift-flux model of Zuber & Findlay (1964) predicts gas holdup,  $\epsilon$ , in vertical flow according to the equation

$$\bar{\epsilon} = \bar{W}_G / [C_0(\bar{W}_G + \bar{W}_L) + V_d] \quad [1]$$

where  $W_G$  and  $W_L$  are the gas and liquid superficial velocities,  $V_d$  is a weighted drift velocity term accounting for local relative velocity between bubbles and liquid and  $C_0$  is a "profile constant" accounting for interaction of the velocity and gas voidage distributions. An overscore denotes that the quantity is averaged over the pipe cross section.

Although the drift-flux model has been applied successfully to gas-liquid upflow using a constant value for  $C_0$ , typically 1.1 to 1.2 (Nassos & Bankoff 1967; Govier & Aziz 1972; Bhaga & Weber 1972; Clark & Flemmer 1984), Lorenzi & Sotgia (1978) and Petrick & Kudirka (1966) concluded that  $C_0$  varied with gas and liquid flowrate. More recent measurements of local void fractions with bubble probes (Serizawa *et al.* 1975; Nakoryakov *et al.* 1981; Galaup 1975; Galaup & Delhaye 1976) have demonstrated that bubble distributions across the pipe diameter will change significantly with increasing gas void fraction, in such a way that  $C_0$  would be low, probably less than unity, at low gas void fractions and would increase in value with increasing gas voidage. Data of Herringe & Davis (1976, 1978) suggest that this change in distributions is not merely an entrance effect.

Using graphical voidage and velocity profiles presented by Galaup (1975), the present authors performed a numerical integration across the pipe diameter; at a water velocity of 1.5 m/sec, and a void fraction of 5%,  $C_0$  was close to 0.9 in value. At higher voidages profile interaction was such that  $C_0$  was greater than unity.

In pipes of larger diameter  $C_0$  is less constant. Whereas all the data supporting the constancy of  $C_0$  were found using a narrow bore apparatus, Hills (1976), using a 0.15 m pipe, and Shipley (1984), using a 0.457 m pipe, found that data did not fall on a single line

on the drift-flux plot. Shipley explained this phenomenon by using a modified drift velocity term, but an equivalent explanation might be based on a variation in  $C_0$ .

#### MODIFIED DRIFT-FLUX APPROACH

Miller *et al.* (1984) found that holdup of air in air-slurry flow was described by a family of curves on a drift-flux plot. They proposed a modified drift-flux equation, using two profile constants. A similar approach is used in the derivation below.

Pursuing an argument after that of Zuber & Findlay (1964),

$$\overline{W}_G/\bar{\epsilon} = (\overline{W}_G\epsilon)/\bar{\epsilon} + (\overline{W}_L\epsilon)/\bar{\epsilon} + V, \quad [2]$$

Setting two profile constants,

$$C_G = (\overline{W}_G\epsilon)/\overline{W}_G\bar{\epsilon}, \quad [3]$$

and

$$C_L = (\overline{W}_L\epsilon)/\overline{W}_L\bar{\epsilon}, \quad [4]$$

the modified three constant drift-flux model becomes

$$\overline{W}_G/\bar{\epsilon} = C_G\overline{W}_G + C_L\overline{W}_L + V, \quad [5]$$

in which case the conventional constant,  $C_0$ , is given by

$$C_0 = C_L\overline{W}_L/(\overline{W}_G + \overline{W}_L) + C_G\overline{W}_G/(\overline{W}_G + \overline{W}_L), \quad [6]$$

and is a function of flowing gas fraction.

#### EXPERIMENTAL

A vertical test section of 4 m length and 100 mm diameter was placed in a two-phase flow loop between two quick-closing ball valves. Air was introduced into the upward water flow 30 diameters before the section through four 8 mm diameter, 500 mm long copper tubes, each drilled with fifty 1 mm holes. Details of the apparatus and techniques used are given by Clark (1985) and Flemmer & Clark (1984).

Mixture velocities ranged from 0.7 to 2.7 m/sec, at gas void fractions from 0.05 to 0.25.

#### RESULTS AND DISCUSSION

The flow, observed through a full bore glass section, fitted the visual description of churn-turbulent flow given by Zuber & Findlay (1965). Bubble sizes ranged from 1.5 to 5 mm in diameter, and occasional larger cap-shaped bubbles were present. Values of the bubble rise velocity relative to the liquid were monitored by measuring the pressure changes in the ullage of the isolated section (Flemmer & Clark 1984), and found to agree with the formula of Harmathy (1960).

Holdup data were plotted on a drift-flux plot of average gas velocity versus total superficial velocity, but were found to be widely scattered about the best fit line. The variation in gas velocity was too great to be explained in terms of varying local slip (drift velocity), and was attributed to inconstancy of  $C_0$ . For each data point, a single value of  $C_0$  was calculated under the constraint of a drift velocity of 0.25 m/sec. Examination of the results revealed that  $C_0$  increased with voidage, as shown in figure 1.

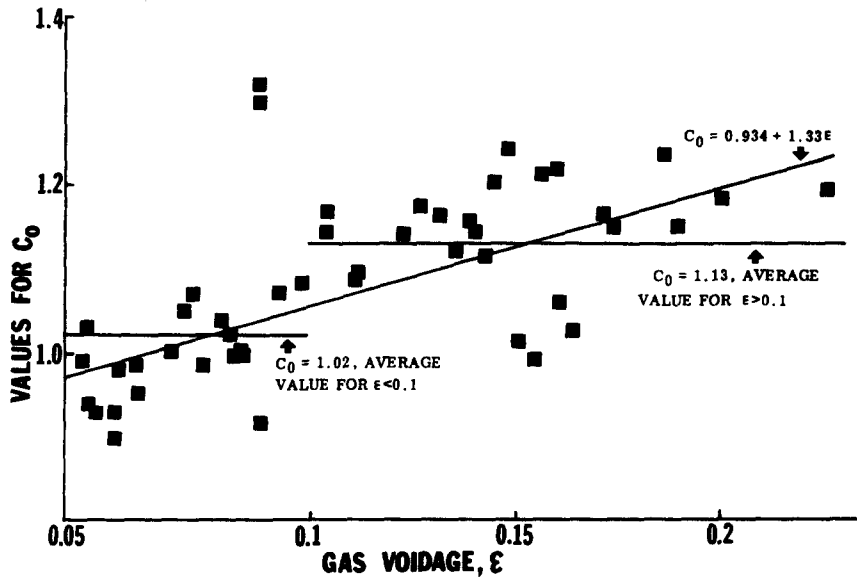


Figure 1. Variation of  $C_0$  with respect to average air void fraction.

Using the three constant model [5] a regression was performed on the data under constraint of  $V_v = 0.25$  m/sec. Values of  $C_L = 0.93$  and  $C_G = 1.95$  found good agreement with the data, as shown on the parity plot, figure 2, and explained most of the scatter which had been found when the conventional drift-flux model was first used. At very low voidages  $C_0$  would be close to 0.93, which agrees with the numerical integration of the distributions of Galaup (1975) discussed above. At higher voidages, near transition to slug flow,  $C_0$  would be close to 1.2, in agreement with most of the literature for churn-turbulent bubble flow.

Although the modified drift-flux approach has succeeded in explaining the data from the 100 mm pipe, although the derivation of the equation is mathematically sound, it is possible that this agreement between theory and experiment is still fortuitous. The values of  $C_L$  and  $C_G$  might both change through the range of bubble flow, by both assuming low values at low voidages, and both assuming higher values at higher voidages. Nevertheless, this new model shows greater capacity for describing the two-phase bubble upflow data than the conventional drift-flux model, and can provide a sound basis for the design of two-phase systems using average flow properties.

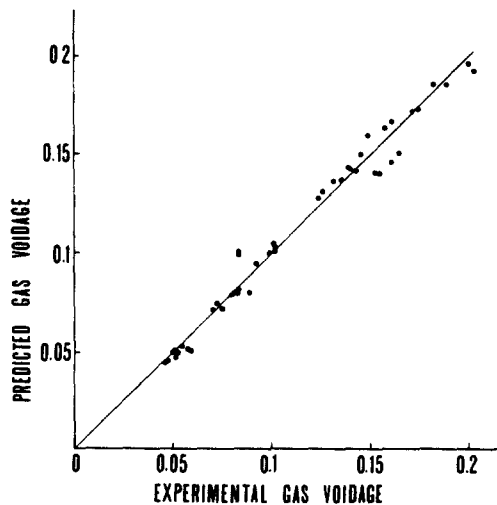


Figure 2. Parity plot of modified drift-flux model with experimental holdup data.  $C_L = 0.93$ ,  $C_G = 1.95$ .

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