

Effect of Addition of Alcohols on Gas Holdup and Backmixing in Bubble Columns

Gas holdup and axial dispersion coefficient data for dilute aqueous alcohol solutions and two different diameter columns at larger gas and liquid velocities compared to those of Schügerl et al. (1977) are presented. Data for cocurrent and batch systems are qualitatively explained using Zuber and Findlay's theory (1965) and bubble structure, and quantified further using a dynamic gas disengagement technique. Unified empirical correlations for the gas holdup and axial dispersion coefficients are presented.

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SCOPE

Applications of bubble columns as bioreactors and for the process of coal liquefaction are relatively recent. Characteristics of the liquid-phase media in these two reactors can be fairly well represented by dilute alcohol solutions. The only work reported on this subject is by Schügerl et al. (1977) for relatively lower gas and liquid throughputs. They propose an empirical correlation for gas holdup involving the bubble diameter which is more difficult to estimate than the gas holdup. They do not propose any correlation for determining the axial dispersion coefficient.

The experimental studies were carried out in two different diameter columns using cocurrent and batch systems. Five aliphatic alcohols (methanol, ethanol, n-propanol, i-propanol, and

butanol) were investigated with concentration varying from 0.5 wt % to 2.4 wt %. The gas holdup was measured using a hydrostatic head technique. The axial dispersion coefficient was measured using heat as a tracer, and was based on the dispersion model. A dynamic gas disengagement method is applied to quantify the bubble-size distribution and bubble-rise velocities. This method involves a measurement of a decline in liquid height as a function of time, after gas flow is suddenly stopped. The experimental data are explained both qualitatively and quantitatively. Empirical correlations for gas holdup and the axial dispersion coefficient, applicable over a wide range of gas and liquid throughputs are presented.

CONCLUSIONS AND SIGNIFICANCE

For dilute aqueous solutions of aliphatic alcohols, a considerable increase in the gas holdup with alcohol chain length was observed. This was found for batch as well as continuous bubble columns. The gas holdup decreased in the following order.

n-butanol > n-propanol > i-propanol
> ethanol > methanol > water

The decrease in surface tension in the presence of alcohols was not sufficient to explain this phenomenon. Bubble dynamics and bubble swarm structure in the presence of surfactant solutions can explain this behavior qualitatively. In the presence of alcohols, the bubbles become more rigid and hence have low rise velocities resulting in a bubbly flow regime up to surprisingly high superficial gas velocities (0.08–0.1 m/s). The decrease in the bubble rise velocities was quantified further using a dynamic gas disengagement technique which gives information regarding the bubble-class distributions (how many sizes of bubbles exist) and bubble-rise velocities. It was observed that

the bubble-rise velocities decreased further with an increase in the superficial gas velocity.

The batch bubble column (BBC) and the continuous bubble column (CBC) exhibit slightly different behavior, probably because of foaming in the BBC. However, all the holdup data can be empirically correlated using the number of carbon atoms in the straight chain as one of the parameters. The holdup model was found to be:

$$\epsilon_G = \frac{0.96 V_G^{0.58} C_N^{0.26}}{(1 + 2.6 V_L)}$$

Axial heat dispersion coefficient results for the CBC show an unusual behavior in the presence of alcohol. This phenomenon can be qualitatively explained using Zuber and Findlay's theory (1965) and bubble structure information. A unified correlation for all the alcohol solutions was possible with the inclusion of the gas holdup as one of the parameters. The correlation is

$$D_L \epsilon_L = 1.42 d_c^{1.33} \left[V_G - \frac{\epsilon_G V_L}{(1 - \epsilon_G)} \right]^{0.73}$$

This infers that the dispersion coefficient and the gas holdup are interrelated.

INTRODUCTION

Recently bubble columns have been tested as bioreactors for the manufacture of single-cell protein and yeast production and used extensively for pilot coal liquefaction reactions. Gas-liquid mass transfer depends on the interfacial area, which in turn depends on the gas holdup, and the optimal operation of the reactor and its productivity depends on the nature of the longitudinal mixing of the phases in the reactor. In coal liquefaction, the gas holdup and the axial backmixing may show an entirely different behavior in the presence of polar molecules in the liquid phase. Panvelker et al. (1982) have recently reported very low values of axial dispersion coefficient compared to the reported ones in the literature. It is considered that dilute aqueous alcohol solutions simulate reasonably well the liquid-phase behaviors in bioreactors (Schügerl et al., 1977) and in coal liquefaction. The only work reported on these types of alcohol solutions is by Schügerl and coworkers (Schügerl et al., 1977; Oels et al., 1978; König et al., 1978); but the relative ranges of gas and liquid velocities studied are low ($V_G < 0.06$ m/s, $V_L < 0.03$ m/s).

In this paper, the work by Schügerl and coworkers is extended in the churn-turbulent regime for a wider range of applications. Two bubble columns, one batch and the other continuous, have been operated at higher gas and liquid throughputs. All the data have been analyzed using different existing hydrodynamic theories in bubble columns. The qualitative explanation was quantified further using a dynamic gas disengagement technique.

LITERATURE REVIEW

The only physical property which differs significantly for water and aqueous solutions of short chain alcohols is surface tension and hence alcohols can be considered as surfactants. As most of the correlations for the gas holdup involve surface tension (Hughmark, 1967; Akita and Yoshida, 1973; Gestrich and Rähse, 1975; Kumar et al., 1976; Mersmann, 1978; Hikita et al., 1980), it can be expected that these correlations would also apply to dilute aqueous solutions. However, controversial results have been reported in the literature (Schügerl et al., 1977; Hikita et al., 1980). Many investigators have used different surfactants to arrive at conflicting conclusions. While Botton et al. (1978) and Miller (1980) reported no effect of surface tension, Schügerl et al. (1977) and Oels et al. (1978) observed a significant increase in the gas holdup with a decrease in the surface tension. Bach and Pilhofer (1978) observed no effect of surface tension on gas holdup for pure liquids, but they noted a different behavior for the liquid mixtures. Hikita et al. (1980) observed higher gas holdup values in aqueous alcohol solutions and could not represent the holdup data for alcohol solutions in their final empirical correlation.

Alexander and Shah (1976) concluded that the surface tension has no effect on the dispersion coefficients. Recently König et al. (1978) measured the liquid-phase dispersion in a bubble column of 0.156 m diameter with aqueous solutions of alcohols. They observed almost step changes in the dispersion coefficient with respect to gas velocity and attributed this behavior to the spatial flow pattern and the structure of the gas phase in liquid dispersion. Rice et al. (1980) predicted that in the presence of the surfactants, the axial dispersion model would be applicable, because of the small size of the bubbles.

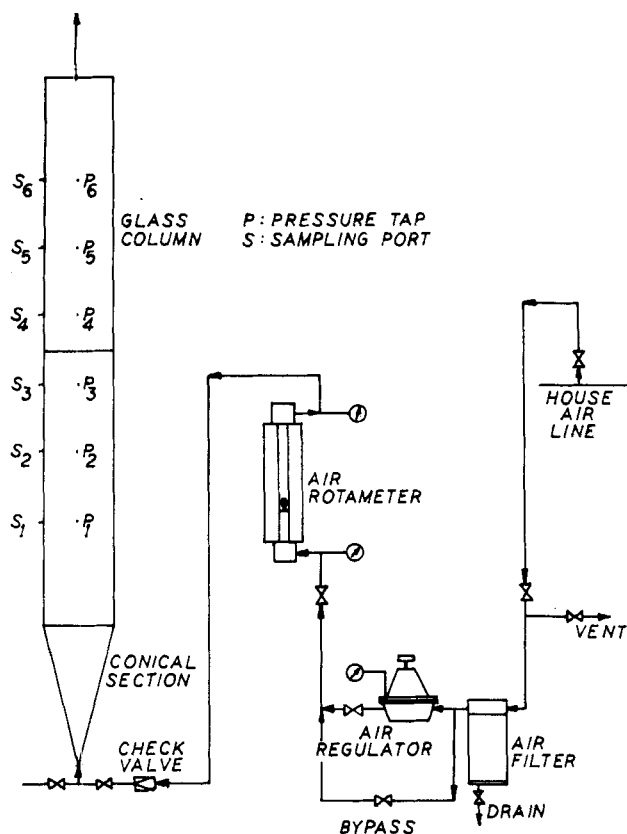


Figure 1a. Experimental Setup for Batch Bubble Column

EXPERIMENTAL SETUP AND ANALYSIS

Experiments are carried out in two-bubble columns at room temperatures ($23 \pm 2^\circ\text{C}$). The geometry and range of operating parameters for these are given in Table 1. The cocurrent bubble column is 0.154 m in diameter and 3.35 m tall, and is made up of stainless steel. It consists of six pressure taps at intervals of 0.61 m which are connected to a manometer. A steam-heated coil connected at the top of the column is used as a heat tracer. Steam is introduced in a continuous fashion, and when the steady state is arrived, the temperature profile is measured with the help of 11 iron constantan thermocouples, located 0.3 m apart from each other, along the length of the column. A shell and tube heat exchanger is located in the outlet line of the column to cool the heated liquid to the desired inlet temperature. The column is insulated with fiberglass insulation material to prevent the heat losses. The details of the experimental setup are discussed elsewhere (Kara et al., 1982). Air is always used as a gas phase. Schematic diagrams for the experimental setups of the continuous and batch bubble columns are shown in Figures 1a and 1b. In batch column, the conical section packed with Berl saddles acts as a calming section to enhance a uniform gas distribution. Pressure taps and sampling ports are located at a distance of 0.3 m along the length of the column. Pressure is measured by pressure transducers. To predict the respective contribution of different bubble sizes in gas holdup value, a dynamic gas disengagement technique is used. This technique involves the measurement of the decline of the aerated liquid height with time, after gas flow in the column is suddenly stopped. This is done with the use of video tape recorder (VTR), a color monitor, and a camera. Frame-by-frame analysis is possible on the VTR with stop action; by knowing the number of frames per second, the height can be determined

TABLE 1. GEOMETRY AND RANGE OF OPERATING PARAMETERS IN TWO-BUBBLE COLUMNS

No.	Type	Diameter	Length	Gas Distributor	Gas and Liquid Operating Ranges (m/s)
I	Batch (BBC)	0.3 m	2.44 m	Perforate Plate (1.6 mm dia. holes)	$0.01 < V_G < 0.3$
II	Cocurrent Continuous	0.154 m	3.35 m	Perforated Plate (1.0 mm dia. holes)	$0.02 < V_G < 0.3$ $0.0 < V_L < 0.15$

EXPERIMENTAL SETUP

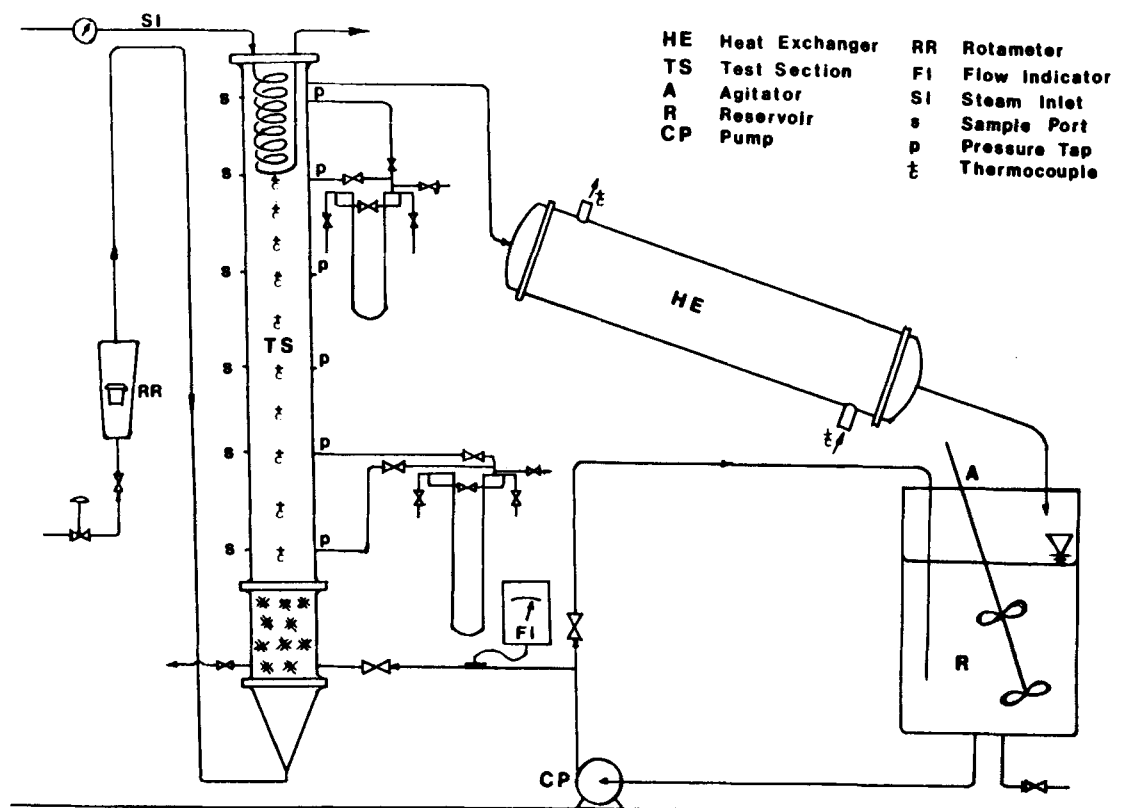


Figure 1b. Experimental Setup for Continuous Bubble Column

TABLE 2. PHYSICAL PROPERTIES OF AQUEOUS ALCOHOL SOLUTIONS

Alcohol	Concentration wt %	Density kg/m ³	Surface Tension N/m	Viscosity Ns/m ² *10 ³
methanol	0.5	997.0	0.070	0.83
	1.0	996.5	0.067	0.83
ethanol	0.5	997.3	0.068	0.83
	1.0	995.0	0.066	0.83
n-propanol	0.5	994.8	0.066	0.85
	1.0	994.0	0.060	0.85
	1.5	993.0	0.056	0.84
	2.4	991.2	0.045	0.84
i-propanol	0.5	994.8	0.066	0.85
n-butanol	0.5	993.5	0.061	0.84
	1.6	991.2	0.049	0.84

as a function of the time. Table 2 gives the physical properties of the systems studied.

Gas holdup is measured with the help of the simple hydrostatic head method. The axial heat dispersion coefficient is measured using the temperature profiles and the axial dispersion model. A steady-state heat balance over a differential cross section of the column yields the following second-order differential equation.

$$-(D_L \rho_L C_{PL} \epsilon_L) \frac{d^2 T}{dz^2} + (\rho_L V_{LCPL}) \frac{dT}{dz} = 0 \quad (1)$$

Implicit in Eq. 1 are the important assumptions that: (1) the contribution due to the latent heat of vaporization is negligible; (2) the thermal conductivity and the density of the gas phase is small compared to that of liquid; (3) molecular thermal conductivity of liquid is negligible compared to the axial dispersion; (4) radial temperature gradients can be ignored; and (5) wall heat losses are negligible. Liquid mixing due to natural convection should be absent since liquid density decreases up the column. Equation 1 is solved analytically using the following boundary conditions:

$$\begin{aligned} @ z = z_C \quad T &= T_C \\ @ z = z_H \quad T &= T_H \end{aligned} \quad (2)$$

By fitting the temperature profile, the axial dispersion coefficient is calculated.

culated. Details of the heat balance are given elsewhere (Cova, 1974; Kara et al., 1982).

Dynamic gas disengagement analysis assumes axially homogeneous initial bubble-size distribution, and no significant bubble coalescence and breakup occur during disengagement. Dynamic gas holdup is measured as a function of time and analyzed using a simplified version of Sriram and Mann's (1977) analysis. For n -distinct bubble sizes, the dynamic gas holdup is given by

$$\epsilon_G(t) = \sum_{i=1}^n \epsilon_{G,i} \left(1 - \frac{t}{t_{\max,i}} \right) \quad (3)$$

The details of the disengagement analysis can be found elsewhere (Godbole et al., 1982).

RESULTS AND DISCUSSION

Gas Holdup

Gas holdup increases with an increase in gas velocity. It is strongly influenced by the type of alcohol present as illustrated in Figures 2 and 3 for CBC and BBC, respectively. The gas holdup decreases in the following order,

$$n\text{-butanol} > n\text{-propanol} > i\text{-propanol} > \text{ethanol} > \text{methanol}$$

The effect of alcohol concentration on the gas holdup is not observed to be significant as shown in Figure 4. The gas holdup decreases with an increase in the liquid velocity but the effect diminishes at higher liquid velocities as evident from Figure 5. This is also indicated by the slightly higher values of gas holdup in BBC. In Figure 6, the experimental values for 0.5 wt % n-propanol are compared with the values obtained with the help of different existing correlations. It can be seen that the experimental values are sometimes twofold higher than predicted by any of these correlations. To understand this unexpected behavior, the bubble dynamics in the presence of surfactants should be clearly understood.

In both the bubble columns, the diameter of the holes of the

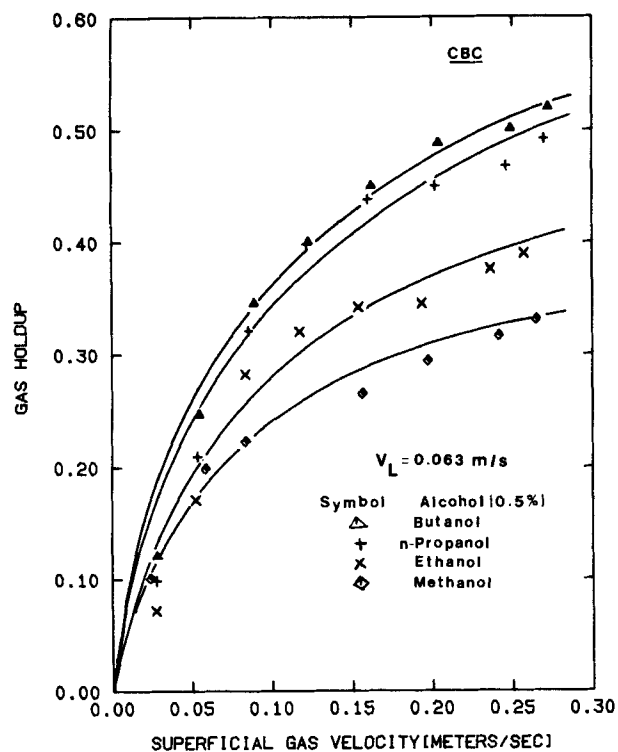


Figure 2. Effect of Type of Alcohol on Gas Holdup (CBC)

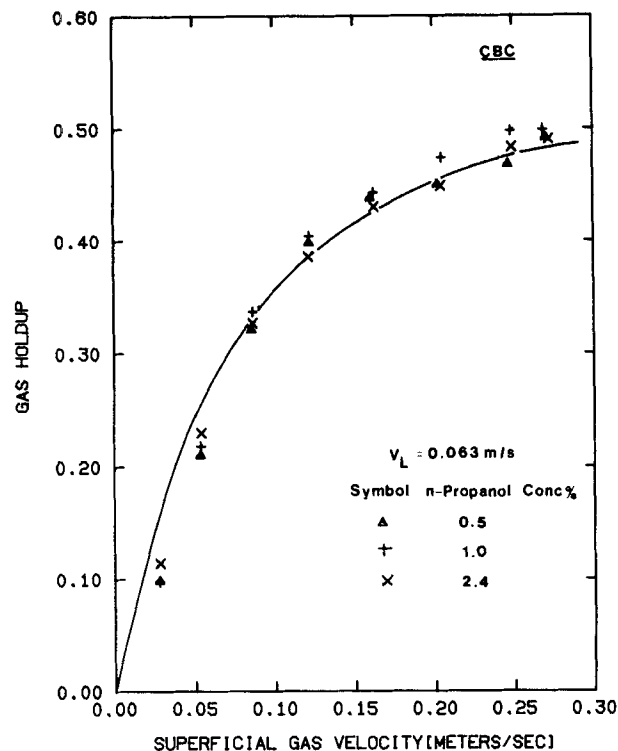


Figure 4. Effect of Concentration of Aqueous Alcohol Solution on Gas Holdup

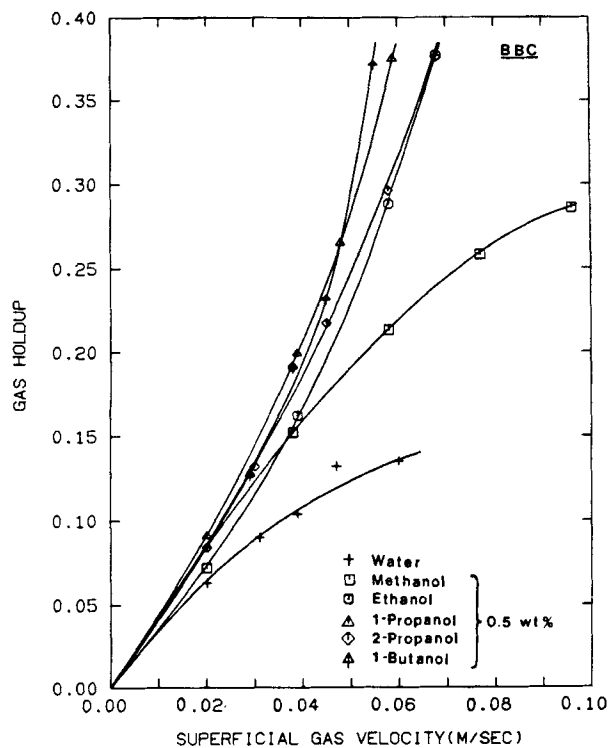


Figure 3. Effect of Type of Alcohol on Gas Holdup (BBC)

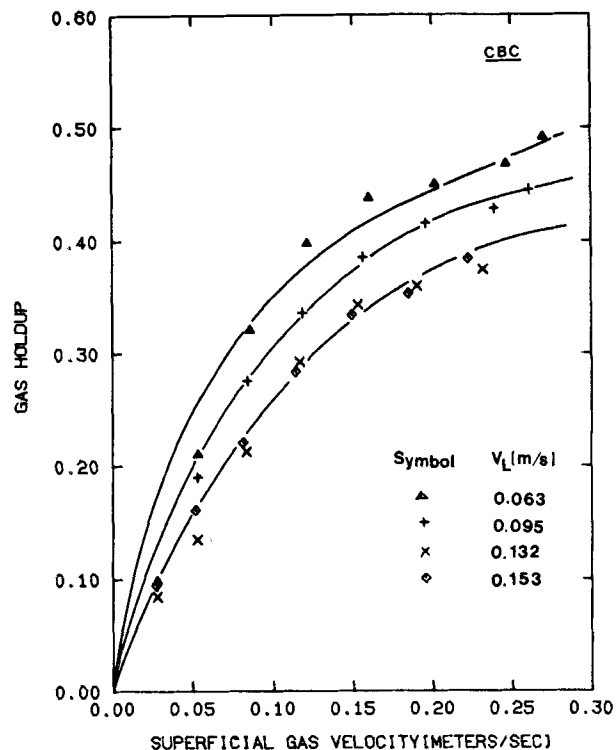


Figure 5. Effect of Superficial Liquid Velocity on Gas Holdup for 0.5 wt % n-Propanol Solution

perforated plates are greater than 0.5 mm, so that bubble size is essentially dependent on the dynamic equilibrium among the buoyancy, drag and the gravitational forces, as indicated by Schügerl et al. (1977). When bubble size is governed by the dynamic equilibrium, it can be calculated by using an equation of the type (Calderbank, 1967).

$$d_B = c \frac{\sigma^{0.6}}{(P/V)^{0.4} \rho_L^{0.2}} \quad (4)$$

where c is constant, and (P/V) is the power per unit volume. In the case of bubble columns, the power input is directly proportional to the gas velocity; therefore, for a particular gas velocity, the bubble size shall essentially depend on the interfacial tension. As evident from Figure 4, when surface tension is varied using different concentrations of the same alcohol, similar results for gas holdup are obtained. This indicates that probably for the same bubble size, the hydrodynamic and backmixing characteristics can

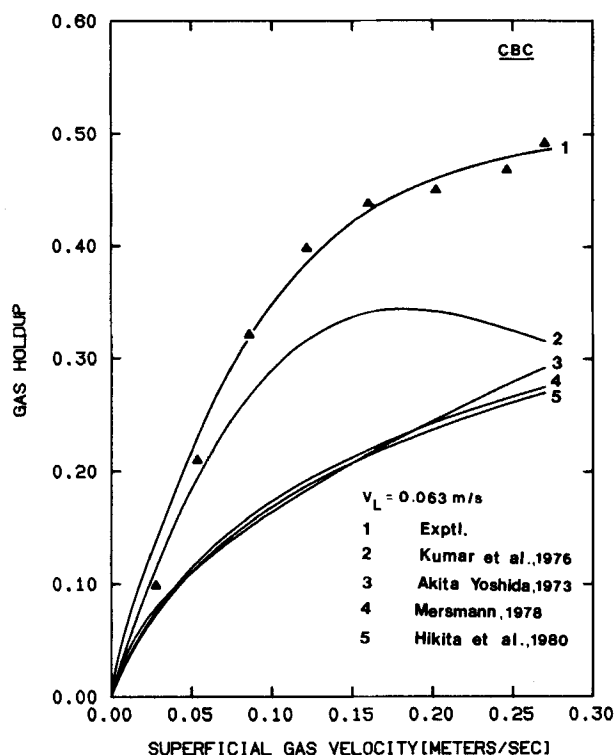


Figure 6. Comparison of Literature Correlations with Experimental Results for 0.5 wt% n-Propanol Solution

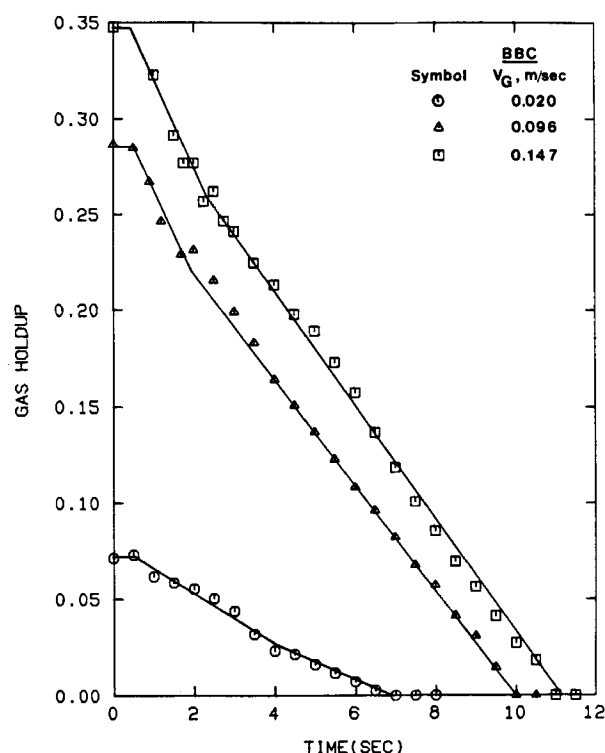


Figure 7. Dynamic Gas Holdup as a Function of Time for 0.5 wt% Methanol Solution

be different, and there is some other fundamental bubble property which governs these characteristics.

The bubble behavior in the presence of surfactants has been studied by many investigators (Levich, 1962; Griffith, 1962; Davis and Acrivos, 1966; Gal-Or and Waslo, 1968; Raymond and Zieminski, 1971; Levan and Newman, 1976; etc.). It has been observed that the presence of the surfactants reduces the bubble-rise velocity significantly. In addition, the presence of alcohols also induces a noncoalescing tendency in two-phase flow (Bridge et al., 1964; Calderbank, 1967). Levich (1962) reported that the presence of alcohols reduces the rise velocity and the effect of an alcohol increases with its surface activity. He further added that it is more pronounced for hexyl and octyl alcohols and the weakest for n-butanol. This effect cannot be related either to changes in surface tension or to corresponding bubble motion. To explain this behavior, Levich (1962) proposed that the surface-active substances tend to accumulate at the interface between the bubble and the liquid, and when a bubble moves through the liquid, adsorbed surface active material is swept to the rear, creating a concentration gradient and hence surface tension gradient which opposes the tangential shear stress. This phenomenon increases the drag on the bubble and hence reduces the rise velocity (Clift et al., 1978).

Davis and Acrivos (1966) proposed that the internal circulation is highly asymmetric with the rear portion forming an essentially stagnant "cap." The relative size of the cap can be determined by a dimensionless group (Bond number) containing a difference between the surface tension of the clean surface and the value of the surface tension at the point where the surface film collapses. This cap is observed to be immobile or rigid (Griffith, 1962). Levan and Newman (1976) proved this rigidity concept theoretically using a stream function analysis. Oels et al. (1978) categorized the bubbles in three regions depending upon their circulation. They stated that large bubbles are freely circulating, small bubbles behave as rigid spheres, and intermediate-sized bubbles are partly covered by rigid cups. Gal-Or and Waslo (1968) further modified this theory to take into account the presence of other bubbles. By using the "surface cell model," they derived an expression for the bubble-rise velocity. They incorporated a quantity γ in the expression which they defined as a retardation coefficient. γ is a function of the surface tension gradient, and it increases with an increase in the gas holdup

value, while it decreases with an increase in the bubble size. The unusual increase in the gas holdup with an increase in the superficial gas velocity is probably the result of the retardation in bubble-rise velocity and the noncoalescing tendency of the medium.

Lindland and Terjesen (1965) and Raymond and Zieminski (1971) found that after a small amount of surfactant has been added, further addition caused an insignificant change in the terminal rise velocity. It should be noted that they have added the surfactants at the ppm level. For the experimental studies reported here, the critical concentration has been exceeded, where the critical concentration refers to the concentration of alcohol above which there is no further effect of an addition of alcohol on the rigidity of the bubble. Therefore, the concentration does not show any effect on the gas holdup, as shown in Figure 4.

Levich (1962) observed an increase in the drag on a bubble with higher homologs of aliphatic alcohols. This observation is supported by Raymond and Zieminski (1971) who studied the effect of alcohol solutions on the drag coefficient of bubbles. They observed that the velocity of migration of straight chain alcohols increases with the chain length of the carbon atoms; therefore, for the same concentration, the rate of accumulation is higher for alcohols of larger molecular size. Hence, the higher the chain length of the alcohol, the more pronounced is the drag reduction. The attraction between carbon chains of the adsorbate molecules increases with the chain length. Therefore, an increase in the chain length would increase the rigidity of the surface and hence the drag coefficient. This probably explains the behavior shown in Figures 2 and 3.

To quantify this further, the bubble-size distribution and rise velocities are measured using a dynamic gas disengagement method. The gas holdup during the disengagement, was plotted as a function of time. As shown in Figure 7, two bubble classes are present. The line with steeper slope corresponds to the holdup of large and small bubbles, while the line with lesser slope corresponds to the holdup of small bubbles. Therefore, by extrapolating the line with lesser slope to the time zero, the holdup due to small bubbles is calculated; hence, by knowing the overall gas holdup, the holdup due to large bubbles can be calculated. It was found that for butanol, propanol and ethanol solutions, only a unique bubble size in Table 3, are obtained. Table 3 clearly shows that the values of

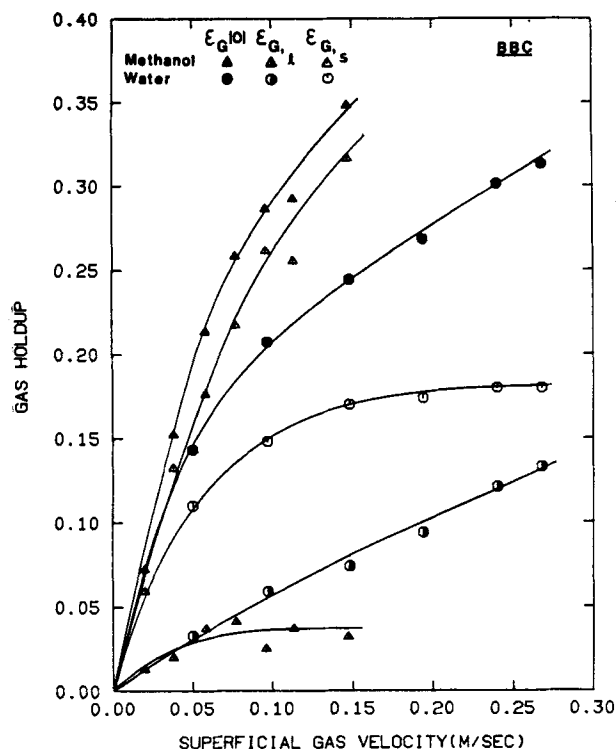


Figure 8. Comparison of Respective Contributions of Small and Large Bubbles to Gas Holdup for 0.5 wt % Methanol and Water

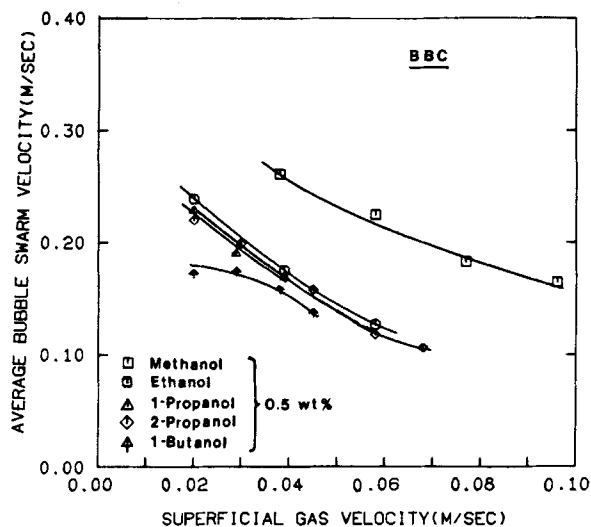


Figure 9. Effect of Type of Alcohol on the Average Bubble Rise Velocity

existed, while for methanol solutions two bubble sizes were present. Figure 8 shows the overall gas holdup along with the gas holdup due to large and small bubbles for 0.5 wt % methanol and water. It can be seen that the contribution due to small bubbles to the overall gas holdup in the case of methanol solution is much higher than the one in the case of water. This indicates that even for methanol solutions, the bubbles are less coalescing compared to water. Bubble-rise velocities are plotted as a function of superficial gas velocity, Figure 9. The average bubble-rise velocities show a consistent pattern to the gas holdup and they increase in the following order,

n-butanol < n-propanol < i-propanol < ethanol < methanol

It can be seen that the single bubble rise velocity shows a 50% increase while going from n-butanol to methanol at comparable gas velocities.

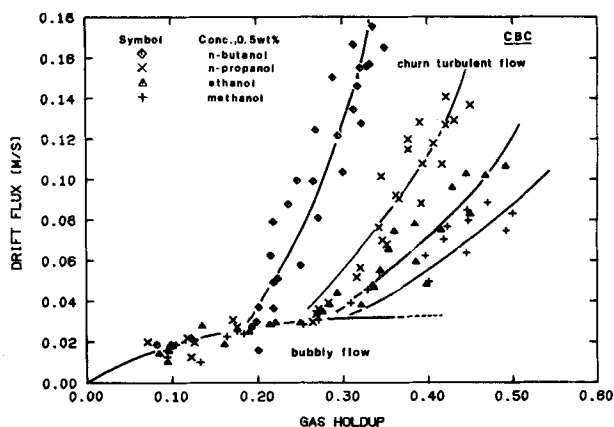


Figure 10. Effect of Type of Alcohol on Transition of Flow Regime

MODELS OF FLOW BEHAVIOR AND GAS HOLDUP

To see the flow regime in which most of the data lie, the flow regime diagrams for CBC are prepared, where the drift flux as a function of gas holdup is plotted. The drift flux of the gas is defined as the volumetric flux of gas relative to the surface moving at an average velocity. Drift flux j_{GL} can be defined as,

$$j_{GL} = V_G \pm \epsilon_G V_T \quad (5)$$

where the positive sign corresponds to countercurrent flow and the negative sign corresponds to cocurrent flow. As shown in Figure 10, the drift flux diagram clearly shows the transition from the bubbly flow to the churn-turbulent flow. As the chain length of the alcohol increases, the transition occurs at higher gas velocities. The dotted line indicates the direction of the drift flux, if the flooding is avoided and the bubbly flow regime can be maintained. Apparently the bubbly flow regime can be maintained up to a gas holdup as high as 50% in the batch bubble column. Lockett and Kirpatrick (1975) observed a bubbly flow regime up to a gas holdup of 66%, though they have to maintain a stagnant bubble phase.

From the flow regime charts, it is observed that most of the data in CBC lie in the churn-turbulent regime. To analyze the data, a theory by Zuber and Findlay (1965) is used which is designed for the churn-turbulent regime. Zuber and Findlay (1965) modified the drift flux theory for churn-turbulent flow. For cocurrent flow, the final equation of their analysis can be written as

$$\frac{\langle V_G \rangle}{\langle \epsilon_G \rangle} = C_o \langle V_T \rangle + \frac{\langle \epsilon_G j_{GL} \rangle}{\langle \epsilon_G \rangle} \quad (6)$$

where

$$C_o = \frac{\langle \epsilon_G V_T \rangle}{\langle \epsilon_G \rangle \langle V_T \rangle} \quad (7)$$

$\langle \rangle$ indicates the average value along the cross section, and C_o is called a distribution parameter, which is a rough indication of nonuniform radial distribution. If the value of drift flux velocity is constant or very small compared to the value of $\langle V_T \rangle$, by plotting the graph of V_G/ϵ_G as a function of V_T , the value of C_o can be obtained.

Figure 11 shows bubble rise velocity as a function of total-phase velocity for 0.5 wt % n-butanol and methanol. It can be easily seen that most of the data for both the alcohols can be linearly correlated. At low V_T , the data deviate from linearity indicating a transition in the flow regime. It is clearly illustrated from this figure that the slope for methanol solution is much higher than for butanol solution. Even the data for 1.6 wt % n-butanol can be fitted with the same straight line corresponding to 0.5 wt %, indicating relative unimportance of the concentration. When the data for all the four alcohols are correlated using the following equation,

$$\frac{V_G}{\epsilon_G} = C_1 + C_o(V_G + V_L) \quad (8)$$

where C_1 and C_o are constants, the following values, as indicated

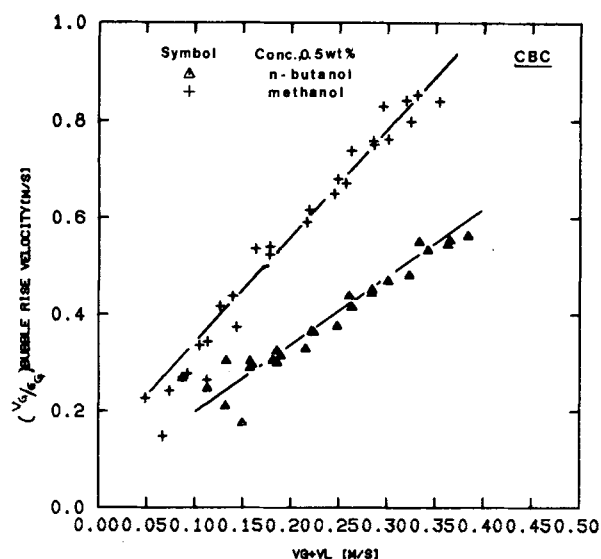


Figure 11. Effect of Type of Alcohol on Intrinsic Gas Phase Velocity (V_G/ϵ_G)

TABLE 3. COEFFICIENTS OF ZUBER-FINDLAY'S EQUATION

Alcohol	C_0	C_1
n-butanol	1.24	0.0604
n-propanol	1.30	0.0663
ethanol	1.66	0.074
methanol	2.41	0.0831

the distribution parameter increase significantly with a decrease in the chain length. It can be concluded that the nonuniformity of the distribution increases with an increase in the chain length, or carbon number. If the value of C_1 is much less than $(V_G + V_L)$, gas holdup can be calculated by a simple relationship as follows,

$$\epsilon_G = \frac{V_G}{C_0(V_G + V_L)} \quad (9)$$

It is observed that for these sets of experiments the value of C_1 is significantly less than $(V_G + V_L)$. The holdup values calculated, based on the above correlation, reasonably ($\pm 10\%$) matched with the experimental data for CBC. This theory is not applicable for the batch bubble column.

The effect of surface tension on the gas holdup is found to be negligible. It is observed that the gas holdup depends on the straight chain length of the alcohols. Therefore, the holdup is empirically correlated with the superficial gas and liquid velocities and the carbon number, which is the number of carbon atoms in the straight chain of alcohol. For example, isopropanol has carbon number equal to two.

An empirical correlation for gas holdup based on 358 experimental points is given by

$$\epsilon_G = \frac{0.97V_G^{0.58}C_N^{0.26}}{(1 + 2.6V_L)} \quad (10)$$

Equation 10 can predict the gas holdup in dilute aqueous solutions of aliphatic alcohols with an average percentage error of $\pm 6.0\%$. This equation should be applicable to any gas distributor for which the bubble size is governed by dynamic equilibrium. If the data are correlated without inclusion of liquid velocity as a parameter, the fitted equation becomes

$$\epsilon_G = 0.75V_G^{0.50}C_N^{0.20} \quad (11)$$

The smaller number of parameters results in an increase in average error ($\pm 8\%$). The parity plot for Eq. 10 is shown in Figure 12.

Dispersion Coefficient

The axial heat dispersion coefficients were obtained using a steady-state method in the CBC. The dispersion coefficient showed

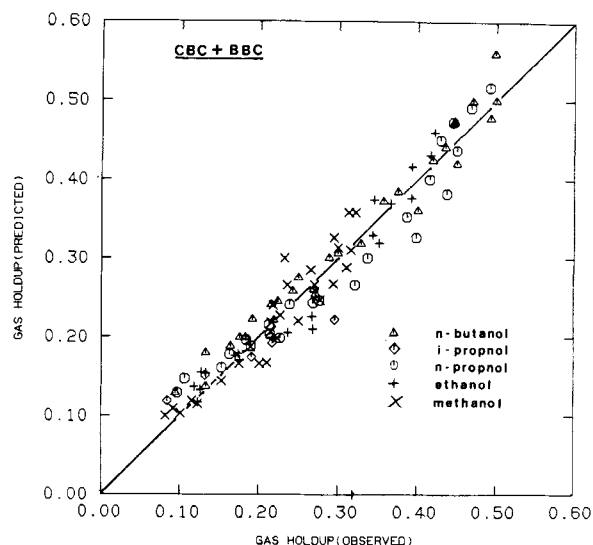


Figure 12. Parity Plot for Gas Holdup

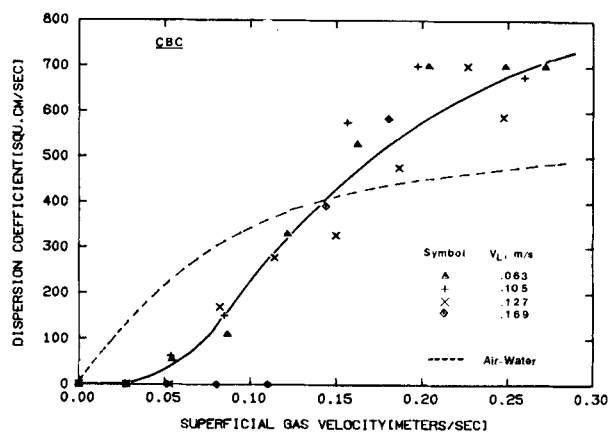


Figure 13. Effect of Dilute Alcohol Solution (2.4 wt % n-Propanol) on the Axial Heat Dispersion Coefficient

a very strange behavior. The dispersion coefficients for 2.6 wt % propanol are shown in Figure 13. The dispersion coefficients are shown as a function of the superficial gas velocity. It is surprising that the value of the dispersion coefficient is negligible at low gas velocities, and can be approximated as zero. These low values are due to the suppression of coalescence. But once the flow enters in the heterogeneous or churn-bubbly regime, the value of dispersion coefficient suddenly shoots up. The values for air-water are also plotted for comparison. Those two curves intersect each other near the gas velocity of 0.15 m/s. It should be noted that the behavior of the dispersion coefficient in the bubbly flow regime is unpredictable. Especially at low liquid velocities, the dispersion coefficient shows a maximum with respect to gas velocity. The effect of liquid velocity at high gas flow rates, however, is insignificant. For a fine dispersion of bubbles, the resulting bubble-rise velocity by Stokes equation (which is already very small for very fine dispersions) is further reduced to a negligible value due to hindering effects of neighboring bubbles. In the domain of high holdup values and relatively fine dispersions, bubbles are completely entrained by the continuous flow (or even by continuous-phase eddies) resulting in a negligible dispersion.

For butanol and propanol solutions, the bubble flow regime is extended up to the gas holdup value of 0.3 to 0.35. So the condition of complete entrainment of the bubbles is satisfied for these two alcohols. At low liquid velocities, probably the liquid eddies are not strong enough to entrain the gas at small gas velocities, but as the holdup increases, those eddies can entrain the gas to show a

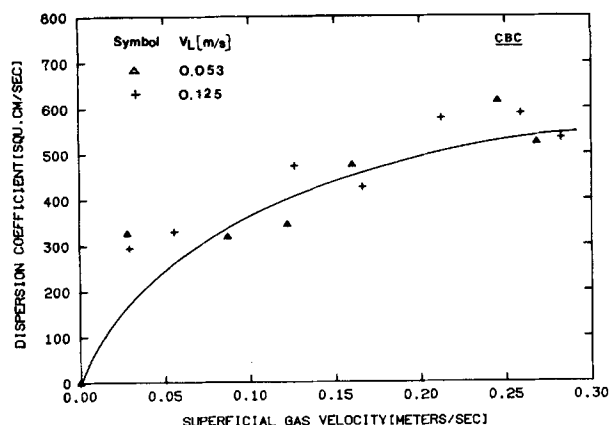


Figure 14. Effect of Superficial Gas Velocity on Axial Heat Dispersion Coefficient for 0.5 wt% Methanol

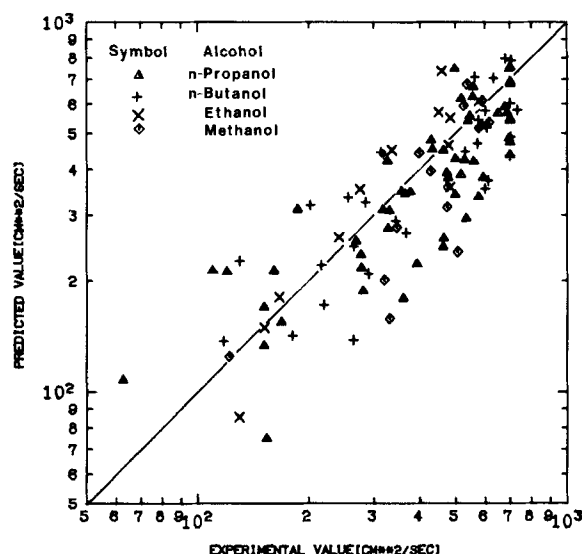


Figure 15. Parity Plot for Axial Dispersion Coefficient

lower dispersion. Additionally, the distribution of bubbles, as indicated by the value of C_o is almost uniform for butanol and propanol solutions; therefore, there is hardly any liquid recirculation due to the lack of nonuniform distribution. The effect of concentration on the backmixing is negligible.

For methanol and ethanol solutions, the behavior is different. The data for methanol solution is shown in Figure 14. The behavior is similar to water, indicating an absence of radial uniformity throughout the range of gas velocity under consideration. The effect of liquid velocity is also negligible. The dispersion values for methanol solution are lower than the propanol solutions at high gas velocities. It should be noted that the dispersion coefficients are based on the overall cross-sectional area. When the dispersion coefficients are calculated based on the available liquid area ($D_{L\epsilon_L}$), and compared with each other; it is found that the type of alcohol is also insignificant at high gas velocities.

An empirical correlation, similar to Baird and Rice (1975), is fitted and the following equation is obtained.

$$D_{L\epsilon_L} = 1.42 d_c^{1.33} \left[V_G - \frac{\epsilon_G V_L}{(1 - \epsilon_G)} \right]^{0.73} \quad (12)$$

The statistical F test shows that 90% of the data fit within $\pm 14\%$ region. A comparison of the experimental and calculated values is shown in Figure 15. It is interesting to note that when the data for the gas velocity greater than 0.08 m/s are correlated with the same equation, the error is reduced to $\pm 9\%$, indicating a relative uncertainty in the bubbly flow regime in alcohol solutions.

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NOTATION

c_p	= specific heat, kJ/kg·K
C_N	= carbon number
C_o	= distribution parameter, defined in Eq. 4
C_1	= constant in Eq. 5
d_B	= bubble diameter, m
d_c	= column diameter, m
D	= axial heat dispersion coefficient, m ² /s
j_{GL}	= drift flux, m/s
(P/V)	= power per unit volume, kg/m·s ³
t	= time, s
$t_{max,t}$	= maximum time required for bubbles of class t to disengage, s
T	= temperature of the liquid phase, K
u_{br}	= bubble rise velocity, m/s
V	= superficial fluid velocity, m/s
V_T	= total-phase velocity, m/s
z	= axial distance, m

Greek Letters

ϵ	= phase holdup
ρ	= phase density, kg/m ³
σ	= interfacial tension, N/m

Subscripts

av	= average
C	= cold end
G	= gas phase
H	= hot end
l	= large bubbles
L	= liquid phase
s	= small bubbles

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PVT Analysis of a New Cubic-Perturbed, Hard-Sphere Equation of State

The cubic-perturbed, hard-sphere equation of state proposed in 1980 by Ishikawa, Chung and Lu, has been analyzed by PVT criteria, as contrasted to the single component and multicomponent vapor-liquid equilibria to which it was applied. The analysis compares its representation of the PVT behavior of substances with that of a simpler equation.

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SCOPE

There have been many different cubic equations of state proposed since van der Waals over a century ago. However, a form was suggested by Ishikawa, Chung and Lu (1980) that had never appeared before in the literature. Because of its novelty, it seemed worthwhile to study it in some detail from the point of view of its PVT behavior which had been examined only on a limited basis when it was presented. In this work it is compared with other cubic equations on seven basic counts: (1) prediction of the compressibility factor at the critical point; (2)

comparison with the general volume-cubic equation of state of Martin (1979); (3) its Z-chart sum; (4) its critical isotherm and prediction of the critical pressure from the critical temperature and volume; (5) its prediction of a collection of PVT data for argon for reduced temperatures from 0.6 to 1.5 and up to twice the critical density; (6) its prediction of pressures from saturated liquid and vapor densities of argon; and (7) the same comparisons for isopentane as for argon where the former has a Z_c of only 0.270 compared to 0.291 for the latter.

CONCLUSIONS AND SIGNIFICANCE

The new equation is shown to predict a low critical pressure and an impossible critical isotherm. When compared to a simpler form of cubic equation of state, it is less satisfactory in representing PVT data up to twice the critical density or in predicting vapor pressure from saturated liquid density for two

quite different fluids, argon and isopentane. Because it was originally utilized largely for its use in equilibrium comparisons, its PVT behavior was not examined. Only in the three-root region is its prediction of a more constant pressure isotherm closer than a simpler equation, but this results from its greater deviation of pressure at smaller volumes. The analysis is useful because it can be applied to evaluate the PVT performance of any equation of state.

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