Structure of Plane Underexpanded Air Jets into Water

An experimental and numerical investigation of the structure of plane underexpanded turbulent air jets in water was conducted to characterize their structure and mixing properties. Measurements included void fraction profiles, static pressure distributions, entrainment rates, and high speed flow visualization. A locally homogeneous flow model was also developed with compressibility effects treated using an effective adapted jet condition. Static pressure measurements confirmed the presence of a shock-wave-containing external expansion region for underexpanded air jets in water, similar to results observed for underexpanded air jets in air. In addition, the plane jets exhibited half-widths (based on void fractions) that were two to three times greater than half-widths (based on scalar properties) observed for single-phase jets. This behavior follows from the strong sensitivity of void fraction to mixing levels due to the large density ratio of the flow. Predictions of void fraction and mass entrainment were encouraging, but performance was found to be sensitive to initial conditions and effects of large-scale unsteadiness near the jet exit.

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Introduction

General characteristics

Although liquid sprays and jets have been studied extensively, relatively little work has been reported concerning high-momentum gas jets injected into liquids. Thus, the objective of this investigation was to study multiphase flow interactions resulting from the injection of air jets into a quiescent water bath. There are many direct applications of gas injection into liquids, including direct-contact condensers, gas dissolution systems, and reservoir destratification systems. In order to avoid unsteadiness, many of these systems operate as underexpanded jets, where the flow is sonic and the static pressure at the jet exit is greater than the ambient pressure. Therefore, understanding multiphase flow properties as they interact with the supersonic wave structure present during underexpanded flow is crucial.

The primary goal of this study was to gain a better understanding of the noncondensing aspects of gas injection into liquids by completing measurements of the flow structure. However, predictions were undertaken as well, to help interpret the measurements and to evaluate the performance of analysis to estimate flow properties. The present study was limited to turbulent plane air jets injected vertically upward into a large still water bath.

For the high flow rates and Reynolds numbers (10^5) considered in the present study, an air core is formed without liquid separation (except during the occurrence of liquid slugging into the passage due to unsteadiness), with subsequent downstream breakup into bubbles of various sizes. Near the exit, the jet is in a forced convection regime with fully turbulent motion causing significant fluctuations near the jet edge. As the jet moves upward, it entrains liquid and thus increases its mass flow. This causes velocities to decrease in the streamwise direction (due to momentum conservation), so that buoyancy forces become more important, giving rise to a transition regime and eventually a purely bubbly plume. Research issues relating to submerged gas injection into a liquid include the shock-wave interaction with the multiphase interface near the jet exit, the turbulent mixing and entrainment properties, and the nature and extent of void fraction (volume fraction of gas) penetration. At present there is no earlier work that includes measurements of void fraction and liquid entrainment velocities for plane underexpanded gas injection into liquids.

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Previous experimental studies

Underexpanded jets occur when the flow at the jet exit is at least sonic so that pressure disturbances cannot propagate upstream of the passage to equilibrate the exit pressure with the lower ambient pressure. Instead, pressure equalization is achieved through a complex external expansion region containing repeating shock cells, having both compression and expansion waves, until mixing has eroded the pattern so that the flow becomes subsonic and the jet pressure remains at the ambient pressure. The appearance of the shock cells in external expansion regions has been widely reported for plane gas injection into gases (Powell, 1953; Sheeran and Dosanjh, 1966).

One important difference between injection of a gas jet into a liquid and the baseline case of a gas jet into a gas is the characteristic unsteadiness associated with gas injection into liquids. This is quite evident for subsonic jets, but has also been observed to a lesser degree for underexpanded sonic round jets by Loth and Faeth (1989), Cho et al. (1986), Lin (1986), Surin et al. (1983), and Ginzburg et al. (1977). Often this unsteadiness results in oscillatory gas release and slugging of liquid into the jet passage, causing appreciable fluctuations of static pressures at the jet exit, as well as within the liquid beyond the jet boundaries (for round jets see Chen and Faeth, 1982; Lin, 1986; and Kerney et al., 1972). This can lead to flow pinch off in the near injector region (Loth, 1988) and can cause potential blockage of the flow passage for reacting two-phase flows, as observed by Avery and Faeth (1974). Avoiding these difficulties is the main reason for using underexpanded conditions when injecting gas into liquids.

The underexpansion ratio of a jet, $\dot{m}/\dot{m}_s$, is defined as the mass flow rate, $\dot{m}$, divided by the mass flow rate for a sonic jet with equal exit and ambient pressures, $\dot{m}_s$; or equivalently, the exit static pressure, p_e, divided by the ambient static pressure, p_∞. Although high underexpansion ratios are used to eliminate liquid slugging, there is some evidence which suggests that the unfavorable bubbling exit condition may be present to some extent even at high underexpansion ratios, as noted for round air jet injection into liquids by Oryall and Brimacombe (1976), Mori et al. (1982), and Surin et al. (1983). Additionally, Lin (1986) showed that increasing density ratios also yielded a less stable discharge. Another feature of multiphase jets involves the highly nonlinear variation of the two-phase acoustic velocity (noted by Semanov and Kosterin, 1964, and Wallis, 1969), which probably affects the gas dynamic processes for underexpanded air injection into water. Finally, Borisov et al. (1983) showed that gas-liquid flow mixtures significantly attenuated shock waves passing through the mixture. Obviously, the mixing of an underexpanded air jet in water is quite complex and has many novel features in comparison to underexpanded gas jets in gases.

Earlier studies of underexpanded gas jets in liquids were confined to gross parameters such as penetration distances and liquid temperature profiles downstream of the two-phase flow region of round condensing jets (Weimer et al., 1973; Kerney et al., 1972; Chen and Faeth, 1982). The work of Tross (1974) and Loth and Faeth (1989) are the studies most closely related to the present work since they included measurements of void fraction, dynamic pressure profiles, and entrainment rates for round underexpanded turbulent air jets in a quiescent water bath. The present investigation extends this work to underexpanded plane jets, emphasizing the near-injector region where gas dynamic effects are more important.

Previous analytical studies

Due to the complexity of gas injection into liquds, most earlier analyses of the process have used the locally homogeneous flow (LHF) approximation of multiphase flow theory, where relative velocities between the phases are neglected and the phases are assumed to be in local thermodynamic equilibrium; that is, interphase transport rates are assumed to be infinitely fast. The earliest analyses used integral models to develop general scaling relationships for the flows (Kerney et al., 1972); however, recent work has applied higher order turbulence models in an attempt to estimate the local structure of the flow (Chen and Faeth, 1982, 1983). The approach of Chen and Faeth followed the conserved-scalar approach of Bilger (1976) and Lockwood and Naguib (1975), which had been successful for estimating the scalar properties of turbulent single-phase free jets. A great simplification offered by the combined LHF/conserved-scalar formalism is that consideration of various systems only requires the construction of state relationships giving scalar properties as a function of the extent of mixing, and these state relationships can be found by simple adiabatic mixing calculations.

The governing partial differential k-ϵ-g equations used by Chen and Faeth (1982, 1983) were time-(Reynolds-) averaged and solved using the boundary layer approximations and an implicit marching scheme. Using the turbulence constants provided by earlier studies of single-phase shear flows, the model was used to predict the vapor penetration lengths of both reacting and condensing jets from several independent studies with reasonable success. Sun et al. (1986) modified the LHF analysis of Chen and Faeth (1983) to use mass- (Favre-) averaged quantities and found reasonable agreement between predictions and measurements near the exit of dilute bubbly jets. These predictions were limited to subsonic multiphase jets; however, recent work suggests at least simplified ways to address underexpanded jets. In particular, Chuech et al. (1989) found that the external expansion region of underexpanded air jets in still air could be treated with an effective adapted jet exit condition for estimates of far-field mixing properties of the flow. Applying this approach to underexpanded round air jets in water proved to be reasonably effective, as shown by Loth and Faeth (1989), prompting a present examination of the approach for the near-injector region of underexpanded plane air jets in water.

Objectives

It is clear that further experimental and theoretical study of underexpanded gas jets injected into liquids is needed to provide a better understanding of the flow. The present investigation sought to provide such additional information, limiting considerations to plane air jets injected into still water (as well as into still air, as a baseline), where momentum exchange is the dominant interphase transport process. Specific objectives of the study include:

1. To complete new measurements of the flow properties, including high-speed motion pictures, flash photography, and shadowgraph photography for flow visualization; gamma-ray absorption for void fraction distributions; laser-Doppler anemometry for liquid entrainment rate; and centerline static presure probes for pressure distributions.

2. To apply locally homogeneous flow analysis, in conjunction with a k-ϵ-g turbulence model, to predict the mixing properties of the jet based on equivalent exit conditions.

Experimental Methods

The experimental methods used were similar to those of Loth and Faeth (1989) and will be discussed very briefly; see Loth (1988) for additional details. The test arrangement consisted of a large water-filled tank with glass sidewalls for optical access. The injector was directed vertically upward and could be traversed to measure flow structure to accommodate stationary instrumentation. The plane injector, illustrated in Figure 1, consisted of a 140 cm^3 plenum chamber followed by a flow straightener and screens. The flow then passed through a 6:1 lateral contraction designed to provide a uniform exit velocity across the exit width, b, of 4.8 mm, yielding an 11:1 exit aspect ratio. Plate glass sidewalls provided optical access for flash (1 μm flash duration) photography, and shadowgraphs, as well as high-speed motion pictures (1 frame/ms). The air supply was controlled and metered similar to Loth and Faeth (1989).

Static pressures along the axis of the flow were measured using a 1 mm stainless steel tube with a pressure tap on its sidewall. The tap was adjustably mounted upstream of the convergent section and 120 mm downstream of the jet exit. A capillary purge with a slight excess pressure was used to prevent water from entering the probe. Experimental uncertainties for static pressure measurements were estimated to be less than 15% for the air-air tests and less than 28% for the air-water tests (Loth, 1988). The hydrophone arrangement of Loth and Faeth (1989) was used to investigate possible acoustic feedback, which can enhance mixing of the flow (Sherman et al., 1976). The hydrophone was placed in the tank at a position of $x/b = y/x = 6$, processing an average of 100 power spectral distributions obtained with a rectangular window and a resolution of 40 Hz.

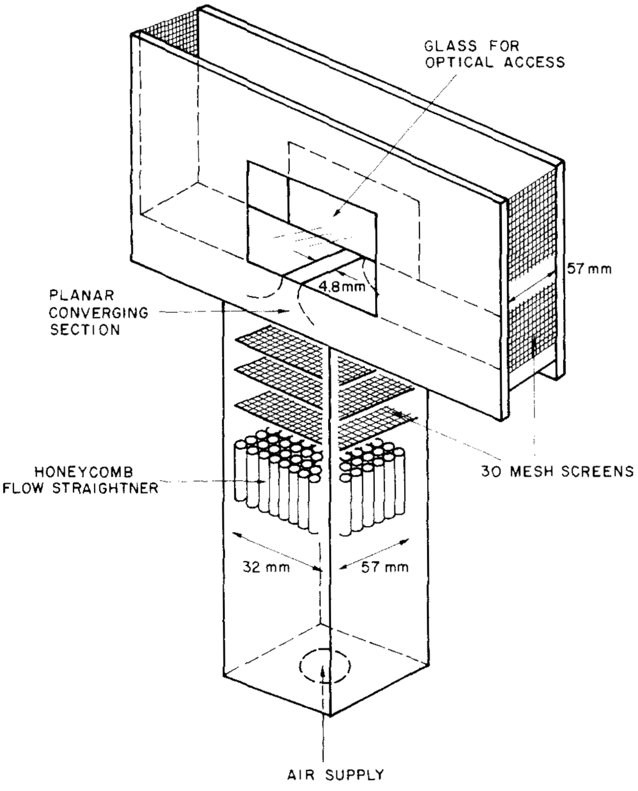


Figure 1. The injector.

The ratio of air volume to total volume at a point is called the void fraction, α, and is of interest because of its relationship to scalar mixing and the overall stucture of the jet. Profiles of time-averaged void fraction were measured using gamma-ray absorption. The arrangement of the instruments and method of analyzing the data were the same as those of Loth and Faeth (1989), except that it was not necessary to deconvolute the data to find cross-stream profiles of void fraction for the present plane jets. Dynamic bias errors, due to turbulent fluctuations along the radiation path, were estimated to be less than 5%, with estimates of maximum experimental uncertainties found to be 9% (Loth, 1988).

Laser-Doppler anemometry was used to measure initial conditions at the injector exit and water entrainment velocities as a function of distance from the injector. The arrangement of the instrumentation and data processing were identical to that used by Loth and Faeth (1989). Maximum experimental uncertainties were estimated to be less than 4% and 25% for mean and fluctuating air velocities, respectively, and less than 9% for mean water entrainment velocities (Loth, 1988).

Jet entrainment rates, defined as the rate of increase of mass flux of the jet with streamwise distance per unit longitudinal length, were obtained from the liquid entrainment velocity measurements of u_∞ and v_∞ using the following expression:

$$d\dot{m}/dx = \rho_\infty(u_\infty \tan\beta_\infty - v_\infty) \qquad (1)$$

where $\beta\infty$ is the angle between the jet boundary and the axis. From this, a dimensionless entrainment coeffieicent can be obtained from scaling laws:

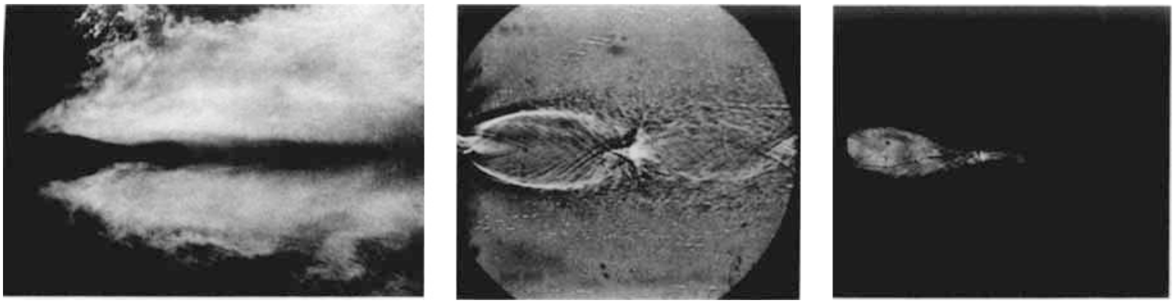
$$Ce = \frac{d\dot{m}/dx}{(F_e \rho_\infty b^{-1})^{1/2}} \qquad (2)$$

where F_e is the jet exit thrust per unit length. Estimated experimental uncertainties of the entrainment measurements were less than 10% (Loth, 1988).

Underexpansion ratios tested included 1.0, 2.0, 3.0, and 4.0. All were below the plane underexpansion ratio of 5 where a normal shock, called a Riemann wave, is formed (Sheeran and Dosanjh, 1966). The sonic exit conditions produced Reynolds numbers of typically 10^5–10^6, and Richardson numbers typically less than 0.002, indicating a fully turbulent jet with negligible buoyancy near the injector.

Numerical Methods

Due to the complex and variable nature of such a flow, there is no theoretical treatment or empirical correlation at present that addresses all the aspects of gas injection into liquids. Therefore, numerical methods using a k-ϵ-g turbulence model previously applied for multiphase jets (Faeth, 1987, and references therein) were employed in this study to extend the evaluation to underexpanded nonreacting gas jets in liquds. This involves solving governing conservation equations for the density, ρ; mean axial momentum, ρv; mean mixture fraction, f (the ratio of air mass to total mass at a given point); turbulence kinetic energy, k; the rate of dissipation of turbulence kinetic energy, ϵ; and mean mixture fraction fluctuations squared, g. It was hoped



A. Flash photograph of air into water B. Shadowgraph of air into air C. Shadowgraph of air into water

Figure 2. Plane injector at $\dot{m}/\dot{m}_s = 3.0$.

that the present simplified analysis would provide insight concerning key aspects of the flow and indicate needed areas of development for future models. A full description of these computations can be found in Loth (1988) and will be described only briefly.

The three major assumptions of the analysis are as follows:

1. Use of the locally homogeneous flow (LHF) approximation to treat multiphase effects;
2. Use of effective adapted-jet exit conditions to treat the external expansion region of underexpanded jets;
3. Use of a higher order turbulence model to treat turbulent mixing

The LHF approximation implies negligible relative velocities between the phases and local thermodynamic equilibrium; therefore the flow is treated like a single-phase fluid having large density variations due to changes in gas concentrations while separated flow parameters, such as drop and bubble distributions, do not enter the formulation. Consistent with present limited knowledge concerning the structure of gas jets in liquids, it seems prudent to evaluate the performance of the LHF analysis, as a baseline, before undertaking the additional complications of separated flow analysis. Furthermore, recent evaluations of the LHF approximation suggest reasonably good performance in the near-injector region of sprays and bubbly jets (Faeth, 1987; Ruff et al., 1989; Sun and Faeth, 1986; Loth and Faeth, 1989).

The effective adapted jet approximation is frequently used to avoid the complexities of treating the gas dynamic phenomena in external expansion regions when estimating turbulent mixing for both single- and multiphase flows (Avery and Faeth, 1975; Birch et al., 1984, 1987; Chuech et al., 1988; Kerney et al., 1972; Weimer et al., 1973). These recent evaluations have also shown that the approach of Kerney et al. is reasonably effective for estimating the structure and mixing of underexpanded gas jets in gases. This involves replacing the actual external expansion process by an instant isentropic expansion to the ambient pressure, and applying the new initial jet width, velocities, and so on, at the original exit plane—ignoring the presence of any virtual origin or further effects of compressibility and preserving the turbulence character of the flow found at the exit.

Due to the high Reynolds numbers of the present flows, some degree of modeling must be accepted to treat their mixing properties. Consistent with past work on gas jets in liquids and related multiphase jets in this laboratory (Chen and Faeth, 1983; Faeth, 1987) turbulent mixing was treated with a simplified *k-e-g* turbulence model. The approach uses mass-weighted (Favre) averages to simplify treatment of density fluctuations, as recommended by Bilger (1976), with empirical constants calibrated for single-phase plane jets (Lai et al., 1986). It is plausible to apply the above treatment for the present geometrically simple high Reynolds number flows, since turbulence models have proven reasonably successful for similar flows.

Other assumptions of the analysis include:

- Steady (in the mean) two-dimensional turbulent flow
- Boundary layer approximations apply
- Equal exchange coefficients of all species phases and heat
- Buoyancy only considered in the governing equations for mean quantities

These assumptions are widely accepted for high Reynolds number turbulent jets where turbulent transport dominates flow properties (Lockwood and Naguib, 1975; Bilger, 1976; Faeth,

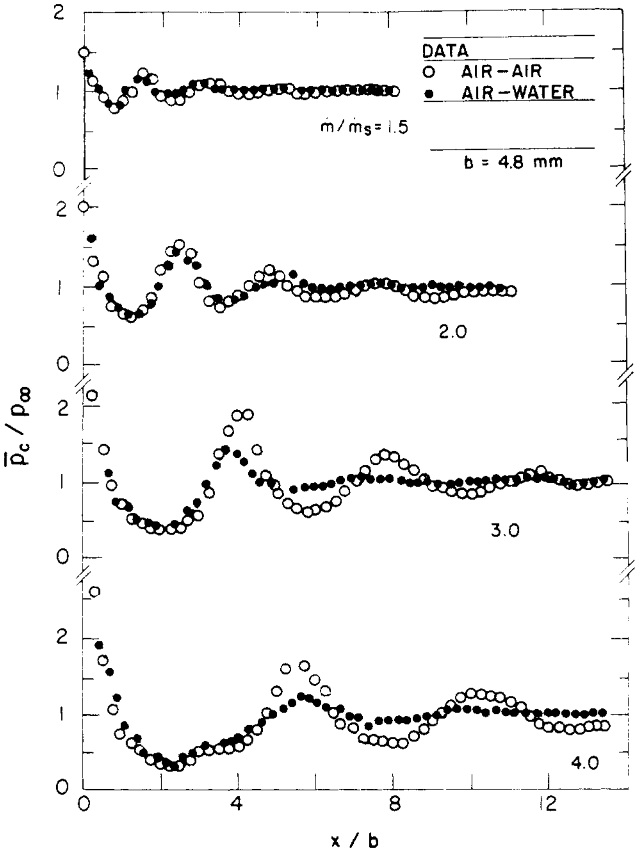


Figure 3. Centerline pressure distributions.

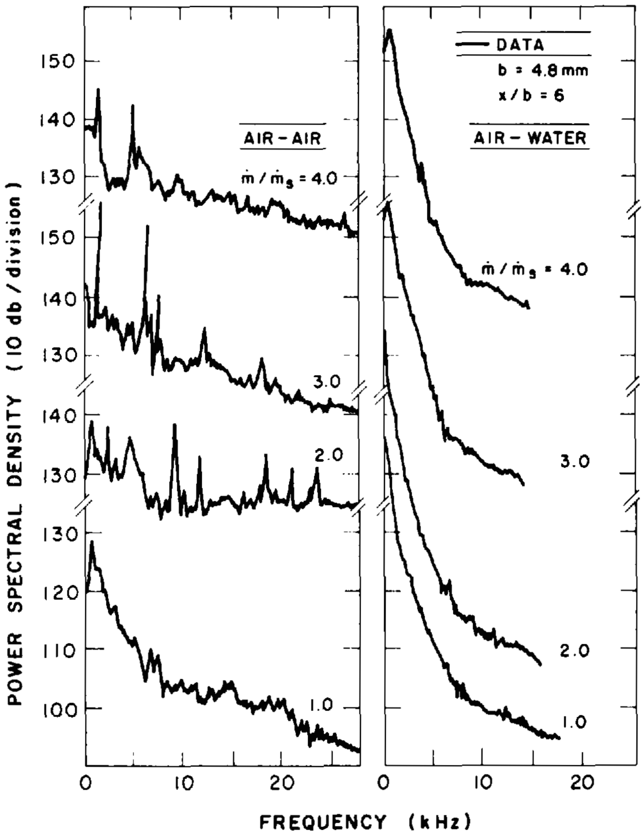


Figure 4. Power spectral density of acoustic signal.

1987). Neglecting buoyancy in the governing equations for turbulent quantities minimizes the empiricism, while past work shows that the effect of this approximation on mean properties is small (Jeng and Faeth, 1984).

Under present assumptions, all scalar properties may be represented solely as functions of mixture fraction, called state relationships, and the conserved-scalar formalism can be used (Bilger, 1976). By definition, the mixture fraction is unity across the jet exit, yielding standard initial conditions. Present measurements, however, suggested enhanced mixing very close to the jet exit due to effects of intrinsic gas-liquid unsteadiness. To represent this effect, a partially mixed initial condition was also considered to reflect the near exit mixing caused by unsteadiness. This involves a void fraction of unity across the core of the flow followed by a region of sinusoidal reduction of void fraction to the ambient value of zero at the edge of the flow. This variation was centered at the equivalent jet exit height and had a thickness equal to 15% of the equivalent jet exit width (Loth, 1988).

The governing conservation equations were integrated using a modified version of the GENMIX algorithm of Spalding (1977). Measured mean and fluctuating jet exit velocities were uniform, with a turbulence level of roughly 3%. Thus, a slug flow profile was used as the initial condition for the calculations. Results reported in the following used 360 cross-stream grid nodes, with streamwise step sizes chosen to be 0.2% of the current flow width, or an entrainment increase of less than 0.2%, whichever was limiting. Doubling the number of nodes in the mesh resulted in less than a 1% variation of flow properties, suggesting that grid resolution was adequate.

Results and Discussion

Flash photographs reveal a clearly irregular jet edge, presumably to the high turbulence levels of the jet itself. A typical photograph is shown for $\dot{m}/\dot{m}_s = 3.0$ in Figure 2A, where the jet is flowing from left to right. The most distinguishing features are the rapid lateral growth of the jet width and the thick multiphase (bubble) layer present. These characteristics may be attributed to the extreme sensitivity of void fraction to low levels of mixture fraction (a mixture fraction of 0.001 typically corresponds to a void fraction of 0.5 for an air/water mixture at atmospheric pressure). In addition, the air jet is observed to quickly entrain droplets within four exit widths downstream. The high-speed (1 frame/ms) motion pictures gave further evidence of the rapid lateral growth of the flow, as well as a characteristic unsteadiness that was found to be an innate part of air injection into water at the underexpansion levels considered in this study. This unsteadiness is markedly different from the slowly evolving large-scale cortex structures observed in single-phase turbulent jets (Antonia et al., 1983). The present large-scale distrubances were random, infrequent, and characterized by sharp interruptions near the exit that induced reverse flow of the gas. Eventually this led to mushroom-shaped disturbances of the jet further downstream. This is similar to

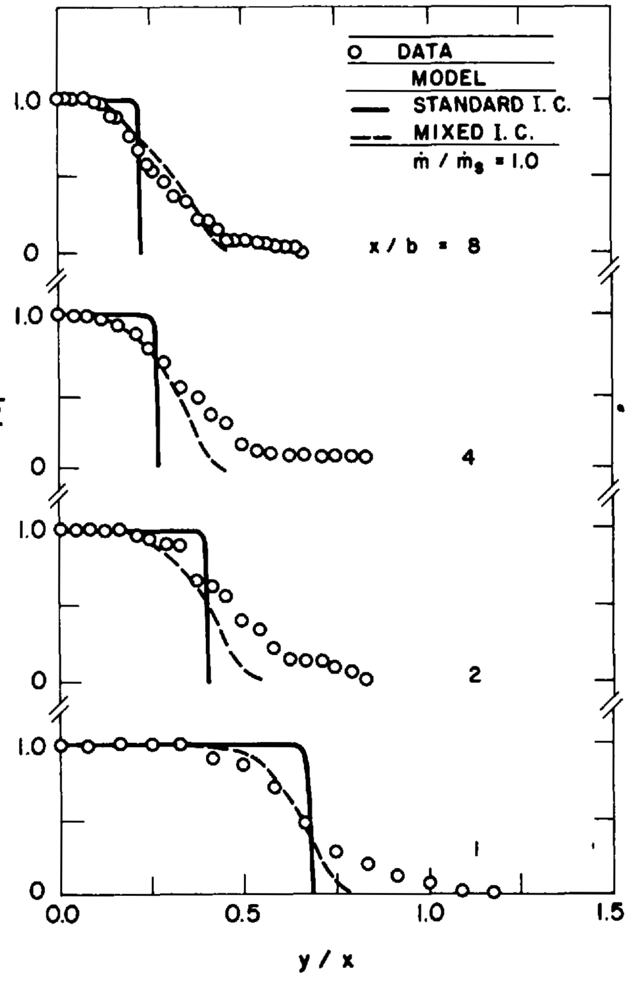


Figure 5. Lateral variation of mean void fraction, $\dot{m}/\dot{m}_s$ = 1.0.

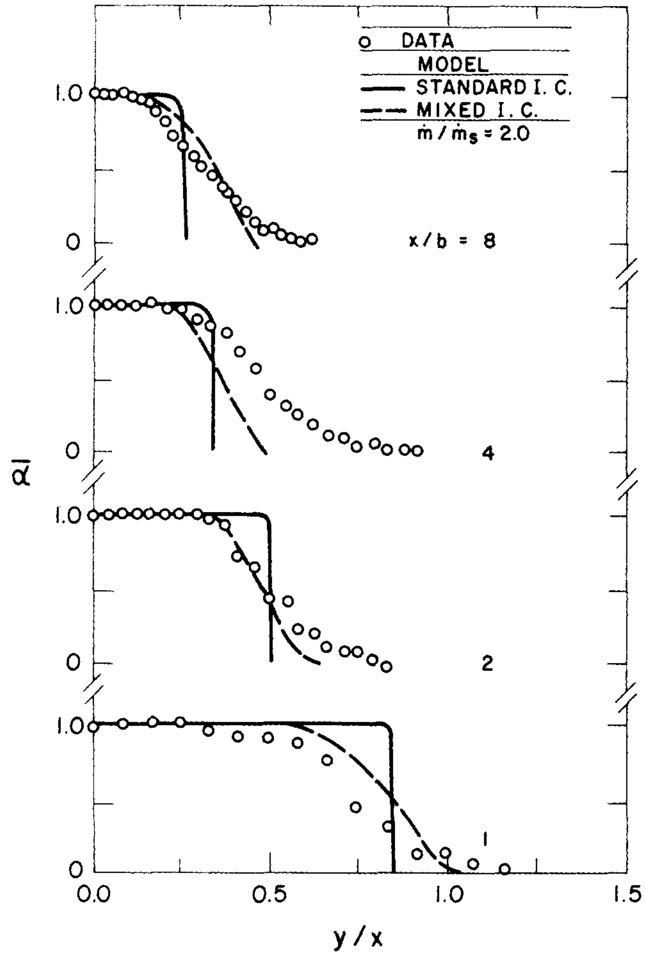


Figure 6. Lateral variation of mean void fraction, $\dot{m}/\dot{m}_s =$ 2.0.

experimental results obtained for round jets by Loth (1988) and Lin (1986), where flow visualization studies indicated that decreased density ratio led to decreased unsteadiness. However, the disturbances found in the present plane jet study were less severe and exhibited little sensitivity to density ratios, possibly due to the stabilizing effect of the end walls.

To investigate the possible gas dynamic region within the two-phase jet, shadowgraphs were taken for both air injected into air and air injected into water. Figure 2B shows the typical underexpanded shock cells for air injected into an ambient air environment for $\dot{m}/\dot{m}_s = 3.0$ and compares quite favorably to similar shadowgraphs taken by Sheeran and Dosanjh (1966). Figure 2C shows the analogous photograph for air injected into water at the same underexpansion ratio. Liquid along the glass walls obscures much of the flow field, however, the similarly shaped first shock cell, as well as some of the compression waves and expansion fans seen in the air-air case, can still be observed. Thus, these shadowgraphs provided the first evidence of the compressible wave pattern within the air core for an underexpanded plane air jet injected into a water.

Static pressures measured along the axis are shown in Figure 3 for all underexpansion ratios for injection into both air and water. The pressure distribution for air injected into air shows the characteristic oscillatory behavior of underexpanded air jets in air, with a moderate decay due to the growth of the shear layer at the jet edge. The shock cell lengths in this case (Loth, 1988) agree to within 15% with those of Sheeran and Dosanjh (1966). For air injected into water, the pressure distribution retains the same expansion and compression behavior as the single-phase jet, but the oscillations decay more rapidly. This further substantiates the existence of the compressible wave pattern in these two-phase flows. The more rapid decay is expected since turbulent mixing is more rapid when a low-density material is injected into a high-density environment (Chen and Faeth, 1982, 1983; Faeth, 1987); furthermore, enhanced mixing would be likely to occur due to the large-scale unsteady disturbances present in the air/water flow.

Acoustic power spectra for both the single- and the two-phase flows were taken with a hydrophone and are presented in Figure 4. Significant effects of acoustic feedback can be seen for the case of air injected into air and can be attribute dto the highly reflective acoustic surface near the injector exit. This is similar to results obtained by Chuech et al. (1989) and Sherman et al. (1976). Based on these findings, acoustic feedback has probably enhanced the rate of decay of the compressible flow field for the air-air case illustrated in Figure 3. However, acoustic feedback does not seem to play a significant role for the air-water jets, presumably due to the nonlinear variation of the acoustic velocity for bubbly flow, which has been shown to attenuate

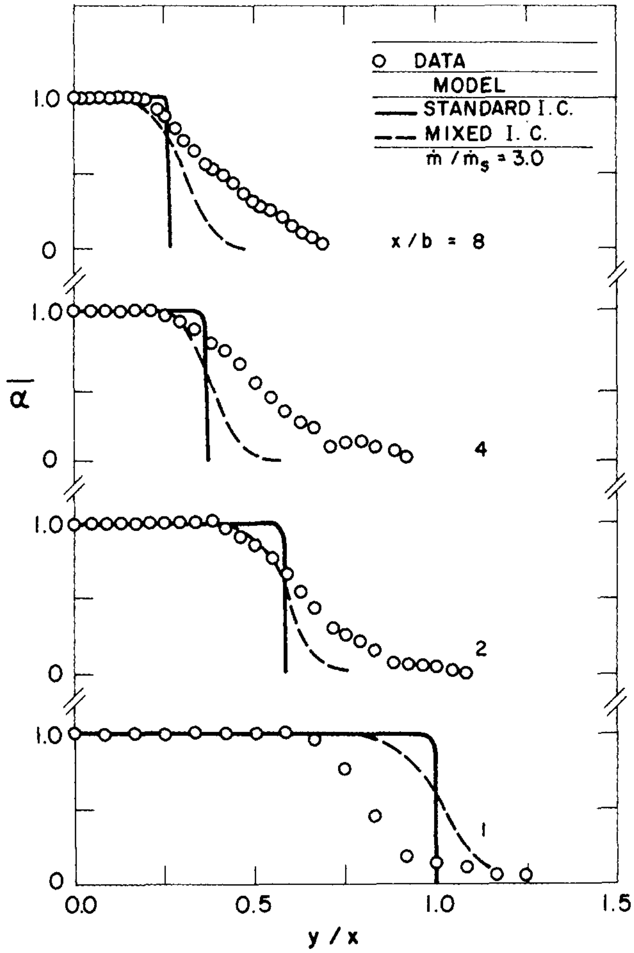


Figure 7. Lateral variation of mean void fraction, $\dot{m}/\dot{m}_s =$ 3.0.

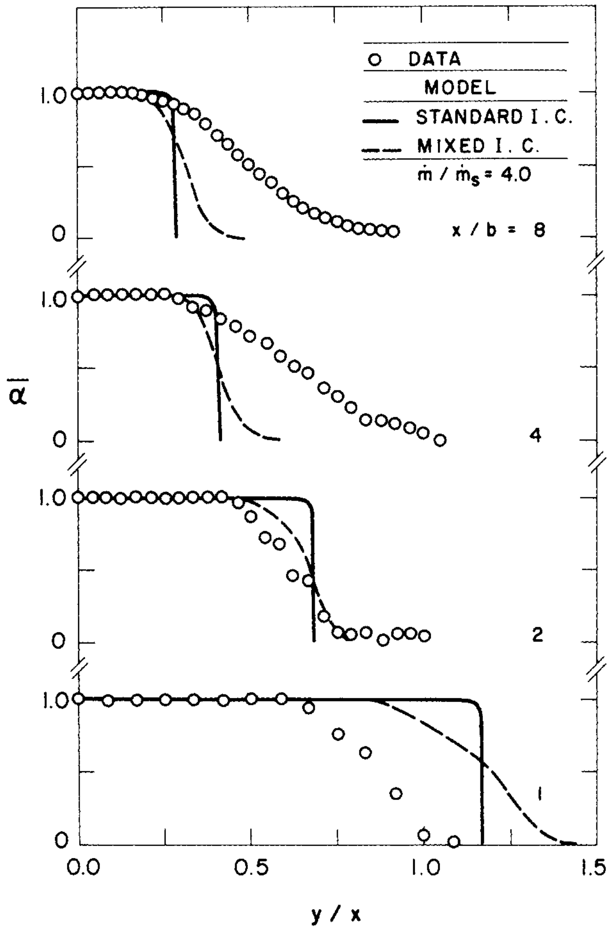


Figure 8. Lateral variation of mean void fraction, $\dot{m}/\dot{m}_s = 4.0$.

pressure waves (Borisov, 1983). Therefore, the previously mentioned two-phase unsteadiness does not appear to be caused by conventional means of acoustic feedback. This would suggest that the near-injector flow field is unstable at these high density ratios and this results in sharp disturbances that eventually lead to large-scale unsteady features of the jet flow.

Measured and predicted lateral time-averaged void fraction profiles for the plane jets are plotted as a function of y/x in Figures 5–8 for various underexpansion ratios. All of the void fraction profiles have unusually large lateral widths ($y/x \sim 0.5$ in the near-injector region) in comparison to widths of single-phase flows ($y/x \sim 0.2$–0.3; Lai et al., 1986, and references therein). This is again attributed to the extreme sensitivity of void fraction to low levels of mixture fraction due to the extremely high density ratio noted earlier. The profile shapes for this near-injector region are, in general, not self-similar: they exhibit the effects of the external expansion region as the underexpansion ratio increases. However, the rather wide multiphase mixing layer appears to have a self-similar profile. Predictions using standard initial conditions exhibit reasonable agreement with measured jet growth of the jet width (based on a void fraction of 0.5) but poor representation of the profile shapes, whereas mixed intial conditions seem to give more reasonable profile shapes. It should be noted that since the LHF approximation is expected to overestimate jet mixing rates, it cannot be responsible for overly narrow estimates of the width of the multiphase mixing layer. Therefore, the innate unsteadiness of the flow, observed by flow visualization, is the likely reason for the increased mixing rates.

Measured jet widths based on a void fraction of 0.5, Figure 9 again show the large jet widths discussed above, even at downstream distances well over 100 momentum thicknesses ($x/b = 10$). Predictions provide reasonable agreement for the low underexpansion ratios; however, discrepancies increase at higher underexpansion ratios. This behavior is again attributed to the inability of a model using effective adaptive jet exit conditions to locally describe the deflection of the liquid surface caused by the pressure field within the external expansion region.

Measurements and predictions of dimensionless entrainment rates are illustrated in Figure 10 for all underexpansion ratios as a function of downstream distance. An empirical relation given by Schneider (1985) for single-phase turbulent jets also appears on the plots. The measurements exhibit a progressive decrease in entrainment rates with increasing x/b and a slight reduction in entrainment rates for increasing mass flow ratios. The first aspect can be found from scaling laws for a fully developed turbulent jet, similar to the trend exhibited by the Schneider relation. The second aspect may be due to both increasd stability at higher underexpansion ratios and the reduced mixing due to compressibility effects at higher Mach numbers (Bogdanoff, 1983; Papamoschou and Roshko, 1986). Predictions using

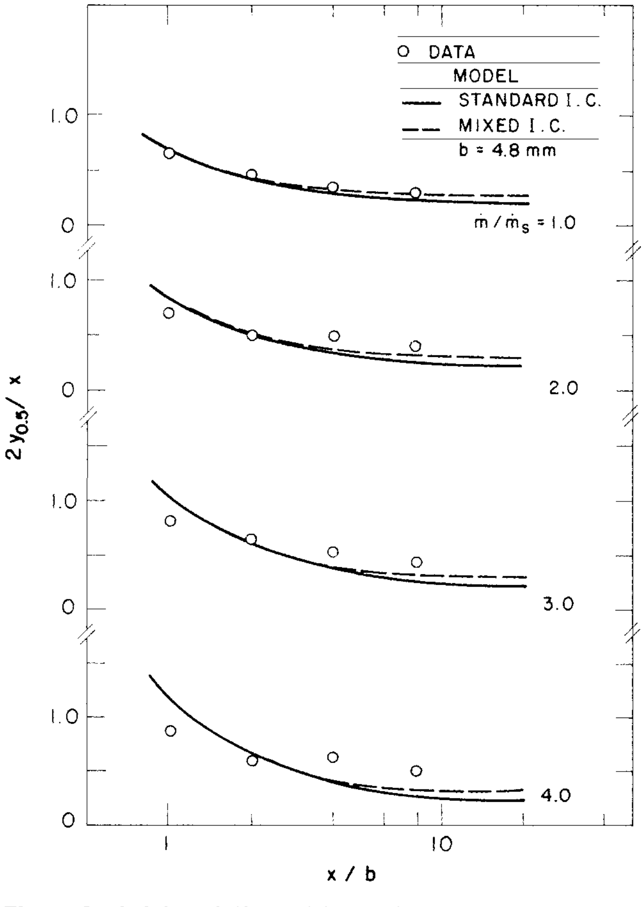


Figure 9. Axial variation of jet width based on a mean void fraction of 0.5.

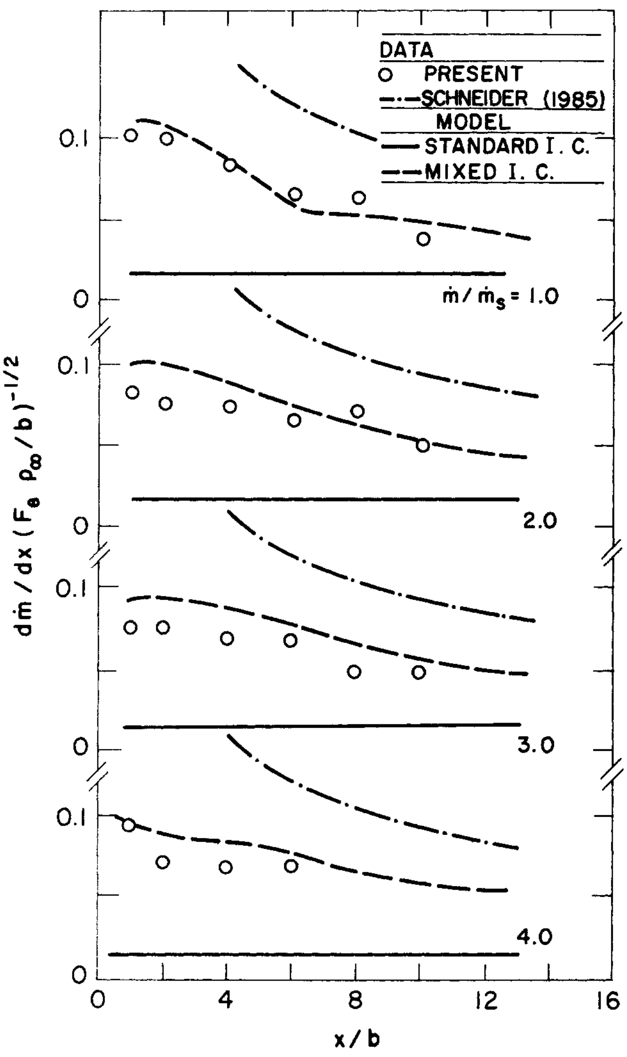


Figure 10. Axial variation of dimensionless entrainment coefficient.

standard initial conditions significantly underestimate the entrainment levels, which may be attibuted to the lack of representation of the innate unsteady disturbances near the jet exit. Improved agreement is found for the predictions with mixed initial conditions, possibly since these initial conditions simulate the effects of the initial flow disturbances that cause significant engulfment of liquid near the jet exit.

Conclusions

The major conclusions of the present study are as follows:

1. Shock-wave-containing external expansion regions are present for injection of underexpanded plane air jets into water, similar to the well-known underexpansion region for air injected into air; however, the more rapid mixing rate for air jets in water causes the external expansion region to decay more rapidly than for air jets into air.

2. Air jets in liquids exhibit unusually large flow widths with a thick multiphase mixing layer, compared to typical single-phase jets. This behavior can be attributed to the strong sensitivity of void fraction to mixing levels.

3. Flow visualization indicated the presence of an innate unsteadiness of the multiphase flow field that is not generally found in typical single-phase turbulent jets. The cause of this behavior appears to be an instability near the jet exit associated with the large density ratios of the two-phase flows.

4. Use of the model based on locally homogeneous flow and equivalent adapted jet exit approximations yielded encouraging predictions of flow properties in spite of the large density ratios and complex mixing characteristics of the present flows. Deficiencies of the predictions are largely attributed to the innate global unsteadiness of the flow and effects of the gas dynamic behavior within the external expansion region. These are challenging problems that must be addressed to improve predictions of the properties of underexpanded gas jets in liquids.

Acknowlegement

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Notation

a = acceleration of gravity
b = jet exit width
C_e = dimensionless entrainment coefficient
f = mixture fraction
F_e = jet exit thrust per unit length
g = square of mixture fraction fluctuations
k = turbulent kinetic energy
$\dot{m}$ = mass flow rate
p = static pressure
R_e = jet exit Reynolds number, $\rho_e F_e b/(\mu_e \dot{m}_e)$
R_i = jet exit Richardson number, $(\rho_\infty/\rho_e - 1)ab/(\dot{m}_e/F_e)^2$
u = axial velocity
x = axial distance from injector exit
y = lateral distance from injector centerline

Greek letters

α = gas void fraction
ϵ = turbulence dissipation
μ = viscosity
ρ = density

Subscripts

c = centerline value
e = initial conditions at jet exit
o = baseline value
s = sonic adapted flow value
0.5 = value at $\alpha = 0.5$
∞ = ambient water condition, edge of jet

Superscripts

$\bar{\ }$ = time-averaged quantity

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