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The Behaviour of Near-Wall Bubble Plumes

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Abstract. *The purpose of this work is to map the three-dimensional behaviour of a bubble plume set to develop near to a wall. Under this condition the plume is observed to bend towards the wall, resulting in a non-axisymmetric configuration. The work presents three dimensional plots of the void fraction profiles. The data is obtained by the electroconductivity technique.*

Keywords*. Bubble plume, Coanda effect, entrainment, void fraction.*

1. Introduction

In previous works on bubble plumes, one of the above authors has focused on a geometrical arrangement consisting of two bubble plumes set side by side (Silva Freire et al. (1999), Silva Freire(2001), Silva Freire et al.(2002)). Under this condition the plumes are observed to attract each other resulting in a bending of the centerline; this phenomenon is known as the Coanda effect. In all these works, a great deal of effort has been placed on the description of features of the gas phase, e.g., the void fraction distribution, the morphology of the bubbles, the rising velocity of the bubbles and so on. A reason for this is clear. The buoyancy dominance of the phenomenon implies that only a perfect understanding of the bubble behaviour will provide the means for the development of any comprehensive theory.

The purpose of this work is to look for experimental evidence to support a new formulation for the entrainment coefficient that is valid when a plume is set to develop close to a wall. Under this condition the plume is seen to develop not axisymmetrically, but deflected sideways - the Coanda effect. The emphasis here is on understanding how the proximity of the wall alters the entrainment coefficient provoking the deflection of the plume. The previous paper of Silva Freire et al.(2002) developed a simple linear expression for the behaviour of the entrainment coefficient, which was then applied to an integral theory. The theory was an extension of the theory of Ditmars and Cederwall(1974), making use of Gaussian profiles and of Boussinesq assumption.

To evaluate the behaviour of the entrainment coefficient, indirect measurements are made through electro-coductivity probes. Results are obtained for the local mean void fraction distribution. The deflection angle of the plumes is then calculated through the mean void fraction profile and is shown to present a logarithmic dependence on the modified Weber and Froude numbers of the flow. A Gaussian distribution for the mean velocity profile, observed to exist for axisymmetric single plumes, is shown not to occur in flow geometries where the Coanda effect is allowed to set in. Photographs of the flow are shown to illustrate the phenomenon.

2. Short literature review

Let us now present a very short review on some important aspects of bubble plumes. As mentioned by Paizis and Schwarz (1975), the rate of entrainment of ambient fluid across a turbulent interface has been defined as the mean rate of increase of turbulent fluid in the flow direction. Indeed, the very rapid spreading of plumes and jets is determined by the capture of surrounding non-turbulent fluid by the turbulence. Townsend (1975) recognizes that the actual entrainment of fluid occurs through sharply defined surfaces by complex processes that must match the correct rate of spread. An important feature of the entrainment rate is its independence on the magnitude of the fluid viscosity; the diffusion process of vorticity across the bounding surface and into the ambient fluid must be accelerated by interaction of eddies of all sizes with the velocity field. A qualitative description of a vorticity transfer model is given by Townsend (1976). In any case, his explanation of the phenomenon cannot be considered definitive since many difficulties still remain to be resolved. Thus, the exact mechanism of the entrainment process is not fully understood.

The flow structure in the near surface region has been primarily studied by Riess and Fannelop (1998) and Friedl and Fannelop (2000). The far field of a bubble plume in shallow water was investigated by Riess and Fannelop (1998). In particular, the influence of the cross-sectional geometry of the channel on the cell structure was investigated experimentally. Flow velocities were measured with a propeller anemometer and an acoustic Doppler velocimeter. The velocity distributions were shown to present a strong dependency on the cross-sectional geometry. For values of the depth-to-width ratio higher than unity the cell length is rather short. In very wide channels three-dimensional effects occur. The flow in the far field is modeled after a an analogy of the surface flow with a free (half) jet with counterflow.

The local elevation of the water surface (the fountain) in a bubble plume was analyzed by Friedl and Fannelop (2000). The article presented a small-scale experimental study to validate a new approximate solution including the effects of gas expansion, slip velocity and turbulent transport. The new model allows for the prediction of the height and width of fountains.

3. The experimental apparatus

The measurements resorted to one basic technique: electro-conductivity sensors. Next, we will comment on it. The working principle of the electro-conductivity sensors is based on the difference between the electrical conductivity (resistivity) of the phases. Since the electrical conductivity of water is much higher than that of air, it is assumed, for practical purposes, that only the continuous phase (liquid) is capable of conducting electrical current.

In a double channel system (whether AC or DC supply), the difference in electrical resistivity between the phases can be sensed by the electrodes in the two-phase flow so that parameters like the local time-averaged mean gas fraction, the rise velocity and the pierced length of bubbles can be obtained through an analysis of the output signal.

The measuring system to be used in this work has been fully described in Barbosa and Bradbury (1996) and in Barbosa (1997); for any detailed information on the system the reader is, therefore, referred to those works. Next we will just briefly comment on the features of the probes.

Co-axial probes were chosen to be used here. In fact, due to its symmetric geometry, the co-axial probe interference on the flow is recognized as being weaker than that of a parallel probe of nearly equal dimensions. The measuring probes were constructed with the following features: i) 0.2 mm diameter stainless steel internal wire (upstream electrode); ii) 0.4 mm OD 0.2 mm ID hypodermic tubing (downstream electrode); iii) length of electrodes free of insulation equal to 0.1 mm; and iv) distance between electrodes equal to 1.5 +/- 0.15 mm.

The experimental apparatus is shown in Figure 1; it comprises a water tank, an air injection system, a 2D traversing mechanism and a data acquisition and analysis system.

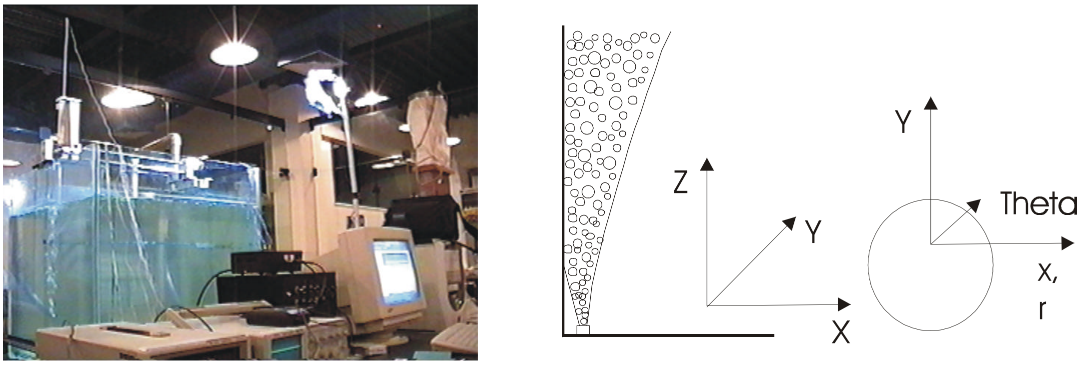


Figure 1. Picture of water tank and sketch of bubble plume near a wall with the coordinate system.

The glass water tank had dimensions 1x1x1 meter and was filled with a 3 gram per liter sodium chloride solution (brine). The air injection system was composed of a mass flow meter and one injection nozzle with a single 3.2 mm diameter hole. The data acquisition and analysis system consisted of a microcomputer with an interface data acquisition board, an oscilloscope, a signal conditioner module and the electro-conductivity probes.

The probe was placed perpendicularly to the tank bottom. The water depth was kept constant and equal to 0.80 m. Table 1 summarizes the experimental conditions examined.

Table 1. Experimental flow conditions.

s [cm]	q [l/min]	F_r	W_e
5.8	1.5 l/min	0.0019	1.1589

The non-dimensional groups are defined accordingly to

$$F_r = \frac{q^2}{gs^5} \quad \text{and} \quad W_e = \frac{Dr\ q^2}{s\ s^3} \tag{1}$$

where g is the acceleration of gravity, q is the gas flow rate issuing from each source, σ is the surface tension and Δρ is the density difference between the phases. The quantities above are, respectively, the modified Froude, F_r, and Weber, W_e, numbers based on the halved distance between the sources, s, or the distance from the wall.

The mean gas fraction at a point in the flow is a time-averaged property given by,

$$f(r,z) = \frac{1}{T}\int_0^T I(r,z,t)\,dt \qquad (2)$$

where T is the total sampling time, I is the digital output signal from the conditioning module and r and z are the co-ordinates shown in Figure 1. The output signal, I, consists of a series of pulses which correspond to the transit of bubbles through the probe. Further details concerning the output signal, I, are available in Barbosa and Bradbury(1996) and in Barbosa (1997).

The data were acquired at a sampling rate of approximately 2.5 kHz and about 50 sampling blocks of 10,000 readings (Barbosa and Bradbury (1996), Barbosa (1997)) were shown to be sufficient to describe the flow at each measured point. In fact, in Barbosa (1997), the shape, size and velocity of the rising bubbles was detailed studied; also, the influence of the injection geometry on plume development and the existence of any lateral wandering motion of the plume were investigated.

The probe calibration was carried out in a vertical pipe with 4 cm diameter and 100 cm length (Figure 2). After the pipe had been filled with water taken from the tank and the probe had been placed in position, a large bubble was carefully introduced at its bottom through a syringe. As the bubble raised and hit the probe, the recordings from a Panasonic video camera were digitalized and analyzed. The pictures that were taken at a frequency of 30 frames per second were then compared with the signal of the conditioning module. The resistance of the flow in the conditioning module was then set so as to furnish the same response in both systems.

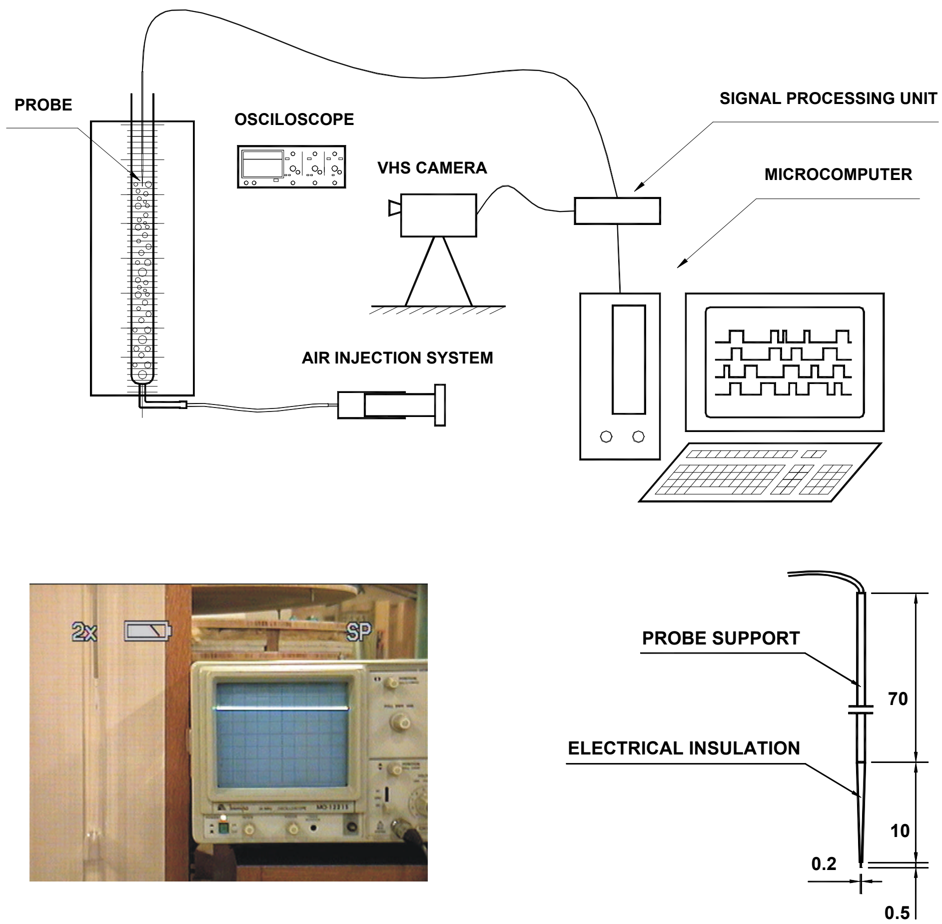


Figure 2. Picture of calibration set up and of the electro-conductivity sensor. Dimensions are in mm.

An uncertainty analysis of the data was performed according to the procedure described in Kline (1985). Typically the uncertainty associated with the mean gas fraction measurements was: f = 0.00035 precision, 0 bias (P=0.95).

4. Results

4.1 Two-dimensional data

For plumes that develop near to a wall, the general flow pattern for both axisymmetric plumes and bent plumes is shown in Figure 3. In the picture, the bending of the plume is clearly illustrated; in fact, and within the experimental conditions of the present work, the plumes are observed to assume a very steady flow pattern, confirming what had been observed by Barbosa and Bradbury (1996) and by Barbosa (1997) for an axysimmetric plume. The photographs shown at Fig. 3 were taken with long exposition times so that they illustrate the mean position of the plumes.

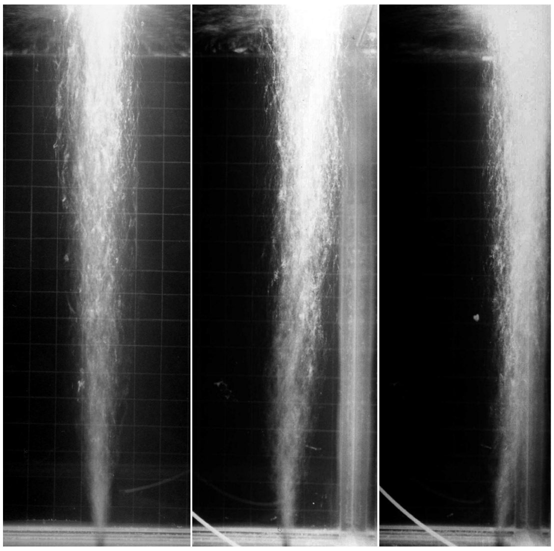


Figure 3. General flow pattern showing plume behaviour near to a wall.

Figure 4 shows local mean gas fraction profiles for six distinct z-stations. The points of maximum mean gas fraction can easily be identified in the figure. They can be taken a reference for the evaluation of the position of the centerline of the plume. From previous studies, we know these points to correspond to the points where the liquid phase velocity is maximum as well. The implication is that a straight line can reasonably approximate most of the trajectories. For the plumes whose distance from the wall is large this trend is particularly well defined.

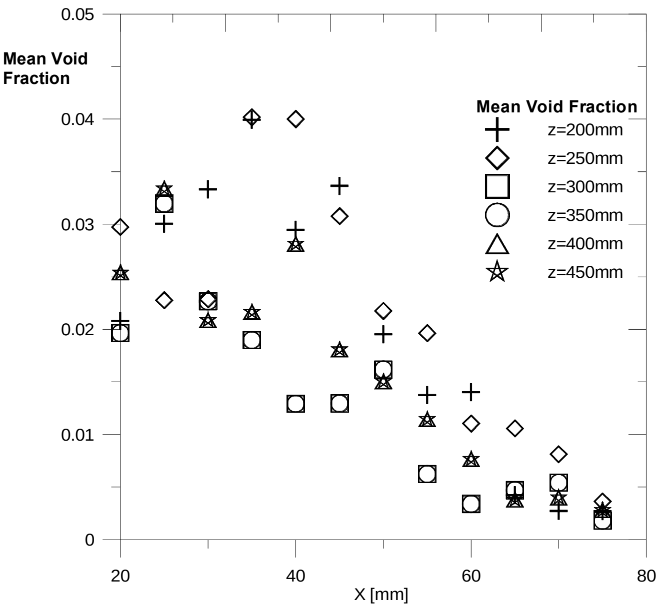
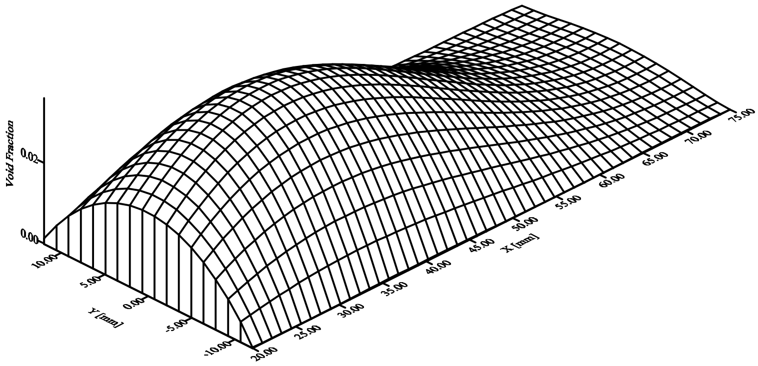


Figure 4. Mean void fraction profiles for several z-stations.

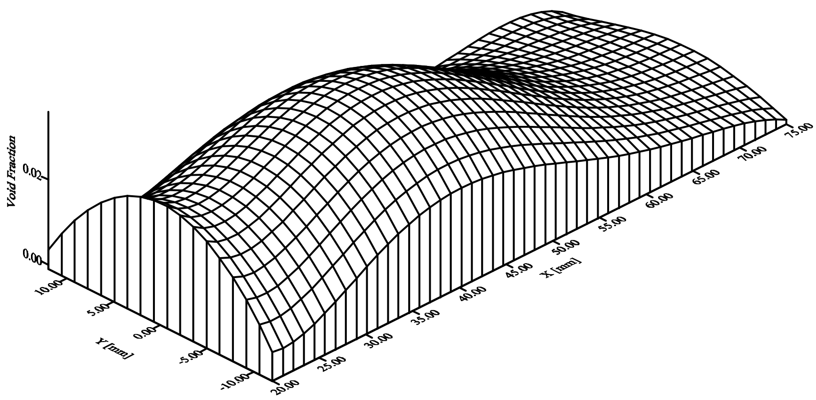
4.2. Three-dimensional data

In this section we will present some three-dimensional mean gas fraction profile data for one selected condition. All three-dimensional data were obtained with the electro-conductivity sensor technique described before. The probe, however, had ten independent wire tips that could be used to yield simultaneous readings. These wires had the form of a spear with ten points. The plane defined by the wires was then traversed perpendicularly to the plane defined by the centerline of the plumes from one end to the other. The tips of the spear were constructed 15 mm distant from each other and were all independently calibrated.

Before considering the three-dimensional structure of the plumes, let us show measurements of mean gas fraction profiles taken in the plane defined by the centerline of the plumes. Figure 5 show the results for stations x = 200, 250, 300, 350, 400 and 450 mm. The mean gas fraction contour lines are shown in Figure 6.

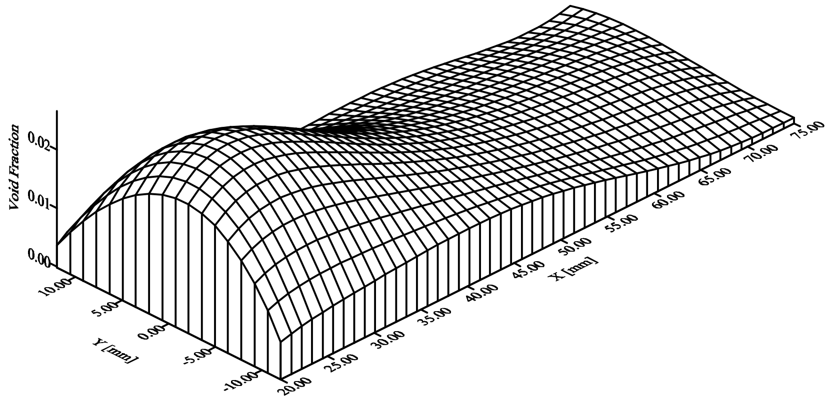


Z=200m

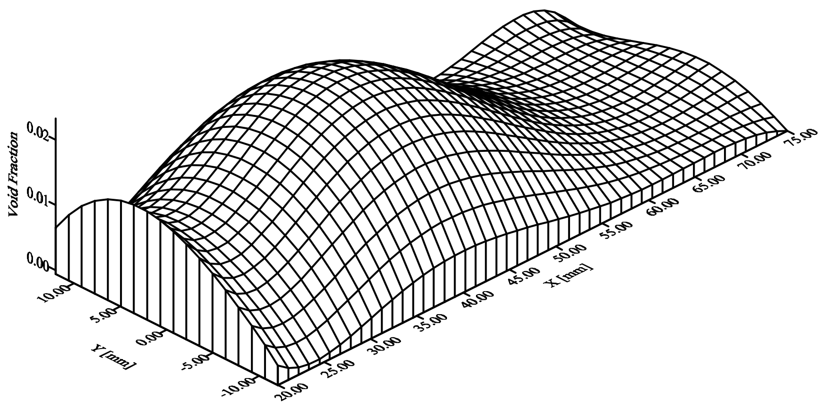


Z=250mm

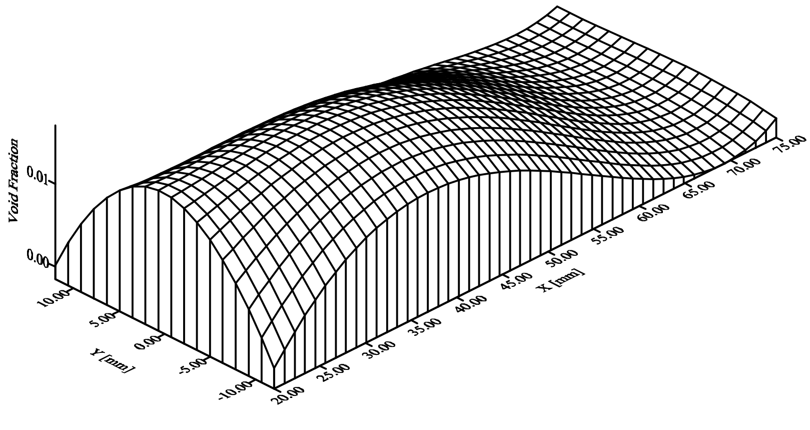
Figure 5. Tri-dimensional void-fraction profiles.



Z=300mm

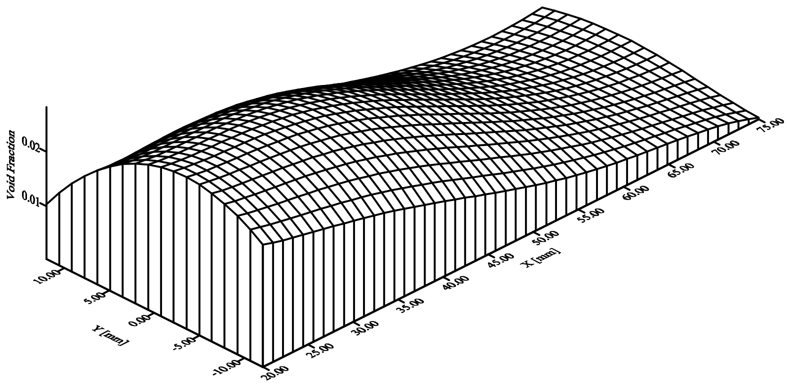


Z=350mm



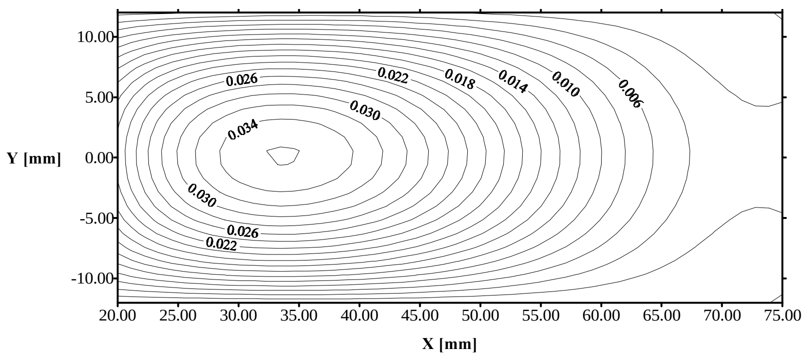
Z=400mm

Figure 5 (continued). Tri-dimensional void-fraction profiles.

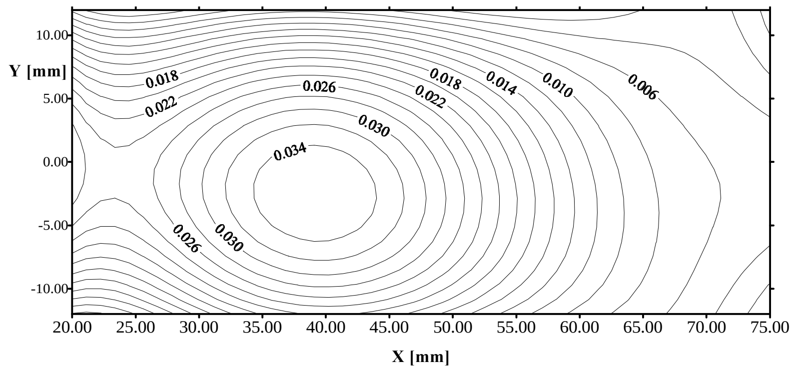


Z=450mm

Figure 5. (continued). Tri-dimensional void-fraction profiles.

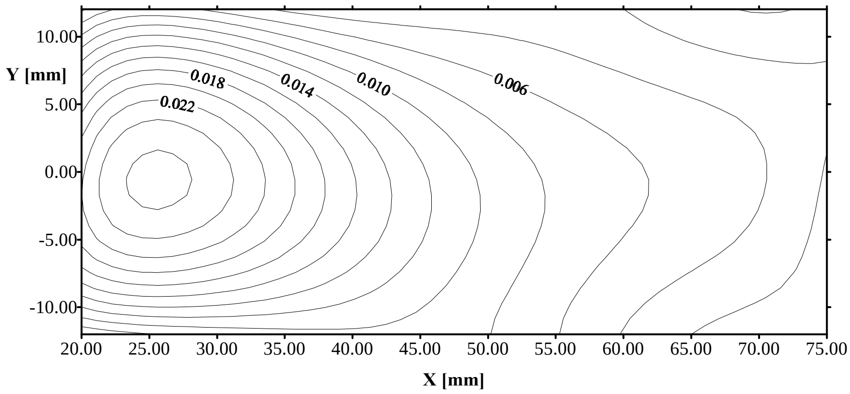


Z=200mm

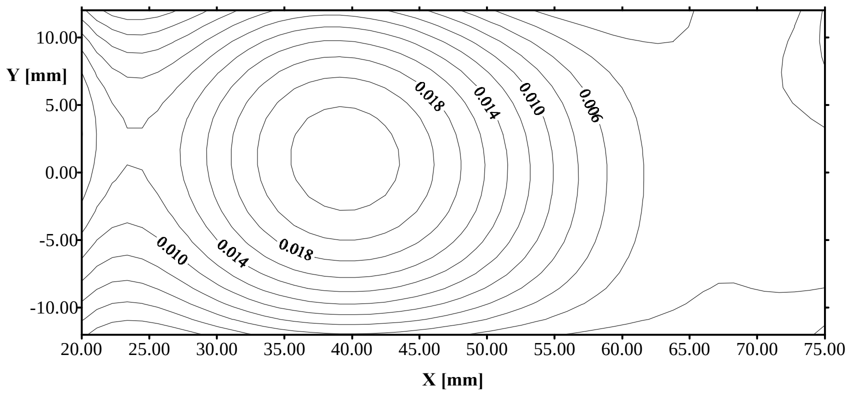


Z=250mm

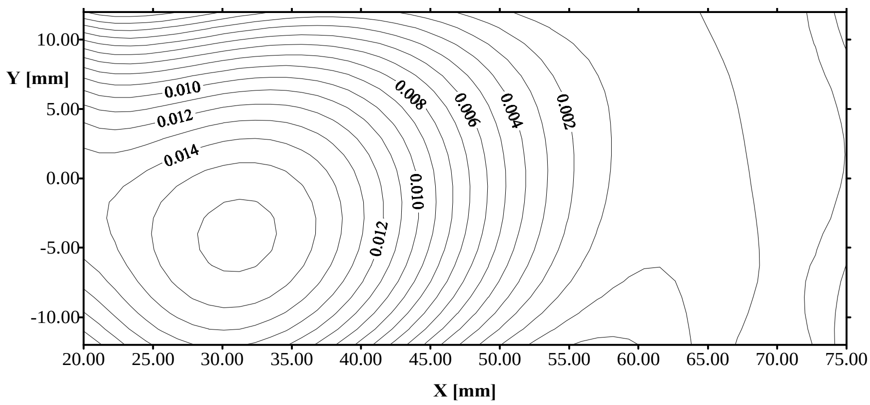
Figure 6. Contour lines of void fraction profiles. Plates show planes defined by Z= 200, 250, 300, 350, 400 and 450 mm respectively.



Z=300mm



Z=350mm



Z=400mm

Figure 6 (Continued). Contour lines of void fraction profiles. Plate shows plane defined by Z= 300, Z=350 and Z=400mm.

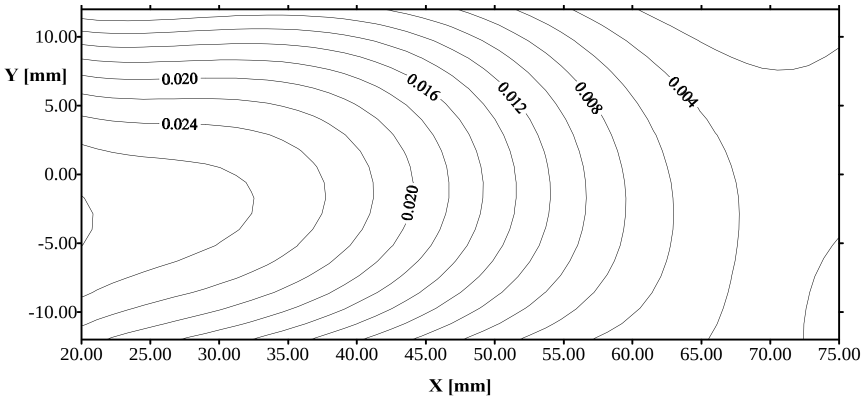


Figure 6. (Continued). Contour lines of void fraction profiles. Plate shows plane defined by Z= 450 mm.

5. Conclusion

The present work has identified some relevant parameters to the problem of a bubble plume interacting with a wall. The work has aimed at characterizing well the void fraction distribution and the liquid phase velocity, using this information to assess the deflection angle of the plume. Also, the authors have tried to develop experimental techniques that can be used in the future to determine values of the entrainment coefficient.

Of course, a limitation of the present theory is its inability no captures any unsteadiness occurring in the flow. As such, the present predictions should be compared with steady data flow. Because the measurements were taken over intervals of 3 to 4 minutes, it is generally considered that the theoretical consideration of steady flow is well reproduced by the experimental data. In fact, no significant wandering motion of the plume was observed which makes us presume that all mean data can confidently be used to validate the theory.

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