BI-PHASE FLOW CHARACTERIZATION BY ULTRASONIC METHODOLOGY

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Abstract. *Gas-liquid two-phase flows are quite usual in industrial processes and demand the measurement of geometric parameters like interfacial area and flow parameters like void fraction. A non-intrusive ultrasonic technique was applied to measure the above mentioned parameters, by comparison of the area under the curve of the frequency spectrum obtained from the ultrasonic reflected pulse on the opposite wall of the column to each different bi-phase flow. The first step was to characterize such parameters to each different bubbly flow studied, applying photographic technique with digital analysis and a specific method to measure void fraction, right away was applied the ultrasonic technique. An experimental system utilizing a vertical bubbly column with an air feed system control and specific equipments to apply ultrasonic and photographic techniques were utilized. The values for the measured variables showed that ultrasonic technique is feasible to detect variations of bubbles swarm, the total cross section area of the bubbles and the void fraction in the liquid column, as well as to characterize bi-phase flows.*

Keywords: bi-phase flow, ultrasound, void fraction.

1. Introduction

The presence of bubbles in industrial processes is originated from problems that are inherent to the utilized equipments and to the process itself. Rotating equipments in general, like centrifugal pumps, if are not designed with a well dimensioned sealing system, or when its components do not present appropriate maintenance, may allow air entrance in the process fluid and, consequently, bubble incorporation to the system. In thermal change systems, in case problems that provoke an imbalance among the thermal energies to be transferred by heat exchanger equipment should occur, by any reason, temperature of the saturation of the refrigerant fluid may be hit, bringing on formation of bubbles, which puts the integrity of the equipment in serious risk.

Both evolution and effectiveness of industrial processes in chemical and petrochemical industries, mainly in processes in which reactors and heat exchanger equipment are used, are closely related to the presence of bubbles in dispersion (liquid gas). Due to quantity and characteristics of the bubbles present in dispersion, a delay of chemical reactions may occur, as well as an inefficiency of thermal changes, which makes the characterization of bubbles something of significant importance.

In nuclear area, bubble characterization is also important, for development of advanced concepts of nuclear reactors depends largely on the amount of available information the designer has about flow type of the refrigerating circuit of the nuclear reactor. Thus, the accomplishment of experimental measurement of fluid flow, to confirm theoretical propositions and validate computer codes, is extremely important on the safety of nuclear reactors (Lamy *et al.*, 1995). In a nuclear reactor, it's necessary to monitor the refrigerating system in order to, in case any bubbles appear, its detection occur fast because, on the other hand, the increase of system thermal energy may cause accident risks.

The objective of this work is to contribute for a characterization of vertical air-water bi-phase flow, thus carrying out data acquisition related to characteristics of bubbles that are dispersed in vertical rising movement in a water column, such as average diameter, interface area and bubble profile, besides obtainable data related to void fraction. For the characterization of bubbles a photographic technique was used and, after the characterization, ultrasonic pulse-echo technique was applied using frequency domain method to verify their sensibility in relation to flow parameters.

2. State of the Art

2.1. Fluid flow regimes

The analysis of physical characteristics of bubbles in a fluid is related to the flow regime in which it is inserted. In literature, in mono-phase flow regimes, the classic division in laminar, turbulent and transitional flows is presented, these being directly influenced by conduit diameter, specific mass, average speed and flow fluid kinematics viscosity.

On the other hand, in the occurrence of multi-phase flows, for instance, liquid-gas, one can see that conduit configuration, either horizontal or vertical one, also influences the flow. In horizontal flows, gas usually lays at the top of the surface of the liquid, whereas in vertical flows, gas disperses in the liquid in form of bubbles.

Under certain process conditions bi-phase flows occur that may present different configurations of gas-liquid distribution along its path. Gas and liquid flows are characterized by non-uniform distribution of their phases and deformable interfaces that, altering themselves along the time, induce to an intrinsically transient flow.

Gas bubbles dispersed in vertical rising bi-phase flow present alternate movement, around an imaginary vertical axis. Due to the physical properties in the environment, air bubbles dispersed in water present spherical and ellipsoidal profiles, occurring in the latter, variations in the relation among the main axes (Liu and Clark, 1995).

The amount of ultrasonic energy reflected by a surface is determined by its local curvature where an ultrasonic beam falls on, that is, the same amount of energy can be reflected either by a small spherical bubble or by a big spheroid bubble (Stravs *et al.*, 1987).

Applying an ultrasonic technique requires a previous characterization of the bubbles present in the flow, since, as cited before, the signal that comes back to the transducer varies in terms of divergence angle (β), reflection coefficient (R), angle formed by beam direction with bubbly interface and bubbly path when crossing the ultrasonic field.

2.2. Studies of ultrasonic application in gas-liquid-type bi-phase flow

Stravs and Stockar (1985) accomplished a study related to ultrasonic pulse-echo technique in order to determine interfacial area in vertical bi-phase flows of the type air-water, comparing it with light alternation technique. Results showed that the ultrasonic technique clearly distinguishes two bubble populations with bubbles of different sizes. In flows with spherical and almost spherical bubbles it was possible to determine reference diameter; however, for ellipsoidal profile bubbles results do not corresponded to the photographic technique.

Chang and Morala (1990) used the ultrasonic transparence technique in a vertical column and a pulse-echo technique in a horizontal conduit for the measurement of void fraction and the interfacial area in air-water bi-phase type flow.

In the horizontal flow data acquisition was carried out from the stratified flow to the slug flow. The obtained results pointed out that it is not possible to measure void fraction and interfacial area in high bubble density flows.

In the vertical flow, the technique used was transparency. When bubbles surpass the speed of 0,2 m/s, a strong re-circulation in the column occur, and the technique cannot be applied due to the big sound generated in the acquisition of signals.

Gonçalves (1991) presented a study related to the measurement of gas and liquid flow in slug flow. The measurement of Taylor's bubbly speed was done using ultrasonic transparence technique. Values obtained for gas and liquid flow with the use of this technique presented results at 35% of the actual value. According to the study, void fraction measurement in bubble flow can only be reliable for attenuation values above 20%.

Hofmann and Bockstroh (1996) accomplished a study of the ultrasonic pulse-echo technique, using applied frequency dominance method in gas-liquid two-phase flow and in solid-liquid in a rectangular vertical column. The objective of the work was to verify the utilization of ultrasound in aggressive media and high temperatures. Results showed it is possible to apply this technique in bi-phase media at water boiling temperature (100°C to 120°C) and in aggressive media like solutions that contain sodium.

Sutin *et al.* (1998) developed a theoretical and experimental study on the volumetric density of air bubbles in bi-phase flow. Through the theoretical study, the authors arrived to proportionality between the non linear spreading field – formed by the interaction among the acoustic pressures of the two frequencies – and the volumetric density of the bubbles which were in resonance when stimulated in the frequency band between 30 and 320 kHz.

Hovart *et al.* (1998) utilized a laser beam generation system to emit ultrasonic pulses. The objective of the work was to study ultrasound sensibility in relation to bubbly flow variation in an air-water bi-phase medium. The study of the ultrasound pulse interaction with the flow was done through the analysis of the wave shape. The absolute average value of signal amplitude, as well as the number of peak pulses of the wave shape, increased with void variation, showing, thus, ultrasound sensibility.

3. Methodology

3.1. Prototype

The experimental development was accomplished in CEFET/RJ's ultrasound laboratory. The developed prototype for the carrying out of the experiments constitutes of a vertical transparent acrylic column, as shown in figure 1.

Figure 1. Column with bubble flow in liquid medium

Bubble formation system was constituted by sets of four stainless steel calibrated orifices, connected at the intermediate base seat. The internal diameters of the utilized orifices sets were: 0,45 mm; 0,55 mm; 0,7 mm e 0,8 mm. In the present work, these calibrated orifices sets will be referred, respectively, as orifices 045, 055, 07 e 08.

3.2 Procedures for data acquisition

Aiming at data acquisition referent to size characterization and profile of the bubbles bringing into relation with the different levels of air flowing out and different internal diameters of orifices, the photographic technique was used.

Five levels of air flowing outs were adopted to each orifice set for the development of the present work. The levels of air flowing out, in l/min were: 0,4; 0,5; 0,6; 0,7 e 0,8.

The areas of the adopted flows were based on the observation of the bi-phase flow in the prototype, so as to apply ultrasound in a bubbly flow regime, in which the gas phase is dispersed in the liquid phase in form of distinct bubbles. Through air flowing out variation, controlled by a rotameter, and through orifice set variation it was possible to obtain 20 different flow parameters. In each flow parameter 10 photos were taken.

3.2.1. Void fraction measurement

Void fraction relates to air quantity in the total volume of the processing liquid; it's an important analysis parameter, as high void fractions indicate the presence of great quantities of bubbles in the process fluid and, also, it can be related to the lack of efficiency in a determined spot of a process plant, or to an equipment inefficiency.

Values of void fraction were obtained relating column liquid levels to air flowing variation used for bubble generation.

3.2.2. Ultrasonic technique

The ultrasonic technique by the frequency domain method consists in the analysis of the ultrasonic beam reflected through the column background wall (background echo). The return signals are influenced by the bi-phase flow, for the bubbles in their ascendant movement through the water column, when passing through the ultrasound field, interact with the spectrum frequency of the transducer, acting like 'filters'.

4 Flow analysis

Analyzing the twenty flow parameters, obtained through the relation among the five levels of air flowing out with the four orifice sets, it was verified that the geometrical shape of the bubbles presented a variation in each parameter. Through the photographic technique with image digitalization, it was observed that bubbles did not present spherical shape, but expanded shapes with elliptical profiles, that stressed more the more air flow and internal diameter increased.

By means of measurement of the main axes of the bubbles, calculations were made to obtain geometric parameters as it is described on table 1 and presented on table 2.

Table 1. Summary of data disposition presented on table 2

N. of bubbles	Relation $d/d_1 = r$
Average spherical diameter (mm) – d_{esf}	
Bubble density (bubbles/cm^2) - ρ	
Total area of the transversal spherical section of the bubble (mm^2) - A_{st}	

Where:

- The number of bubbles represents the total quantity of bubbles obtained in the 10 photos.
- The relation d/d_1 represents the relation (r) between the arithmetic average of the smallest axes and the arithmetic average of the biggest axes of the bubbles
- The average spherical diameter (d_{esf}) was calculated from the average of the smallest axes (d) and from the average of the biggest axes (d_1) of the bubbles, through the equality of the formula of the area of the transversal section of a circular profile sphere with another of an elliptical profile, Eq. (1).

$$\pi.\frac{(desf)^2}{4} = 2.\sqrt[4]{d_1^{\ 2} - d^2}.\sqrt{d_1} \tag{1}$$

- The density of the bubbles (ρ) was obtained through the reason between the quantity of bubbles in each photo and the correspondent photographed area of the longitudinal section of the column.
- The total area of the transversal spherical section (A_{st}) of the bubble was calculated from the average spherical diameter, using the formula of a circle area.

Table. 2 Characterization of air bubbles dispersed in water to different levels of air flow

Orifice	Air flow (l/min)				
	0,4	0,5	0,6	0,7	0,8
045	421 r = 0,741 d_{esf} = 2,673 ρ = 1,05 A_{st} = 2362,2	449 r = 0,718 d_{esf} = 2,797 ρ = 1,12 A_{st} = 2758,2	472 r = 0,719 d_{esf} = 2,776 ρ = 1,17 A_{st} = 2856,7	708 r = 0,743 d_{esf} = 2,647 ρ = 1,76 A_{st} = 3896,1	919 r = 0,762 d_{esf} = 2,571 ρ = 2,28 A_{st} = 4771,0
055	474 r = 0,722 d_{esf} = 2,860 ρ = 1,18 A_{st} = 3045,1	457 r = 0,698 d_{esf} = 2,823 ρ = 1,13 A_{st} = 2860,4	539 r = 0,699 d_{esf} = 2,909 ρ = 1,34 A_{st} = 3582,3	551 r = 0,731 d_{esf} = 3,018 ρ = 1,37 A_{st} = 3941,7	613 r = 0,765 d_{esf} = 3,060 ρ = 1,52 A_{st} = 4508,1
07	164 r = 0,677 d_{esf} = 4,065 ρ = 0,41 A_{st} = 2128,4	202 r = 0,716 d_{esf} = 3,927 ρ = 0,50 A_{st} = 2446,6	237 r = 0,712 d_{esf} = 3,863 ρ = 0,59 A_{st} = 2777,7	245 r = 0,716 d_{esf} = 3,863 ρ = 0,61 A_{st} = 2810,8	369 r = 0,723 d_{esf} = 3,445 ρ = 0,92 A_{st} = 3439,5
08	145 r = 0,681 d_{esf} = 4,320 ρ = 0,36 A_{st} =2125,3	225 r = 0,671 d_{esf} = 3,871 ρ = 0,56 A_{st} = 2648,0	190 r = 0,668 d_{esf} = 4,159 ρ = 0,47 A_{st} = 2581,2	183 r = 0,677 d_{esf} = 4,348 ρ = 0,45 A_{st} = 2717,2	202 r = 0,697 d_{esf} = 4,191 ρ = 0,50 A_{st} = 2786,6

Figure 2 presents examples of four analyzed flow parameters. In the sequence of photos the air flow was maintained constantly, whereas the orifice set varied.

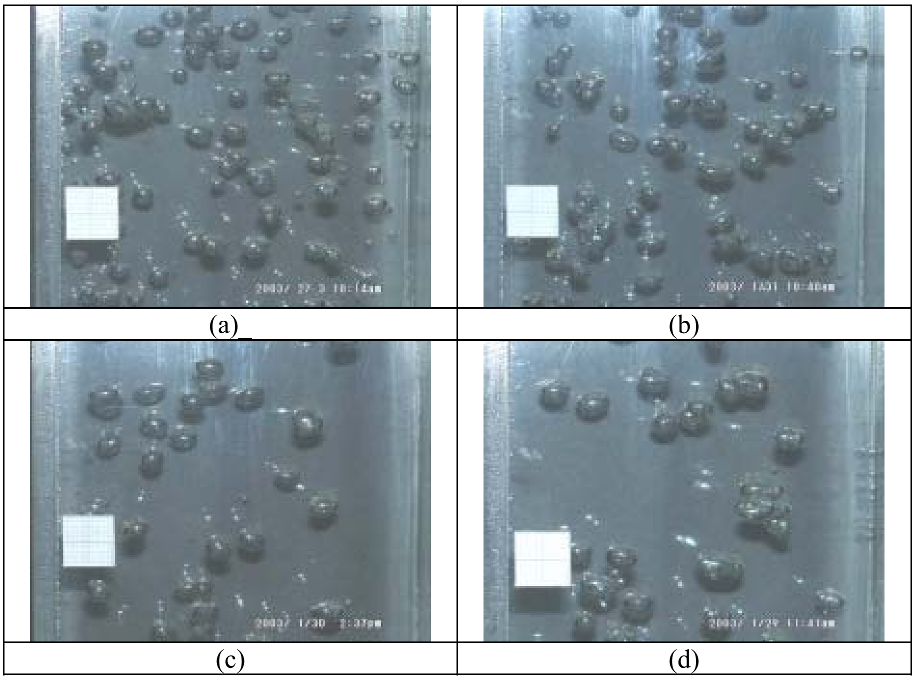


Figure 2. Bubbly flow with air flow of 0,6 l/min utilizing orifice sets: (a) 045; (b) 055; (c) 07 and (d) 08.

Analyzing bubbly flow originated by the orifice set 045 it's verified that the bubbles are small size, have little expanded elliptical profile, and are distributed, most of the path, uniformly, presenting high density along the longitudinal section of the column. On analyzing table 2, one verifies, too, that between the minimum and the maximum air flow level, the biggest variation in quantity of bubbles (184%) and in the total area of the transversal section (102%) occurred.

Establishing a relation between the orifice set 055 with the 045 one it can be verified that the bubbles present a little bigger diameters, a little bit expanded elliptical profile, and a smaller density by area of the longitudinal sector of the column. One can observe, as well, that the distribution of bubbles is less homogeneous, presenting more proximity among them and a bigger transversal section area for a same air flow, with the exception of the last air flow level.

Observing the bubbly flow generated by the orifice set 07, one verifies that bubbles present bigger diameters in relation to the bubbles generated by the previous sets (30% a 43% on average), the elliptical profile is even more expanded, presents an average non uniform distribution, and with low density along the longitudinal section of the column. A bigger closeness occurs, originating instants where bubble layers appear followed by a continuous liquid phase.

Analyzing the orifice set 08 it was verified that, in relation to set 07, bubbles present a bit bigger diameters, more expanded elliptical profile and less density than the orifice set type 07. It's also verifiable that this set presents more closeness among bubbles, a less homogeneous distribution along the longitudinal section of the column and the smallest areas of the transversal section for the same air flow level. Further, it's the set that presented the least quantity of bubbles and the least variation of the area of the transversal section

5 Void fraction (VF)

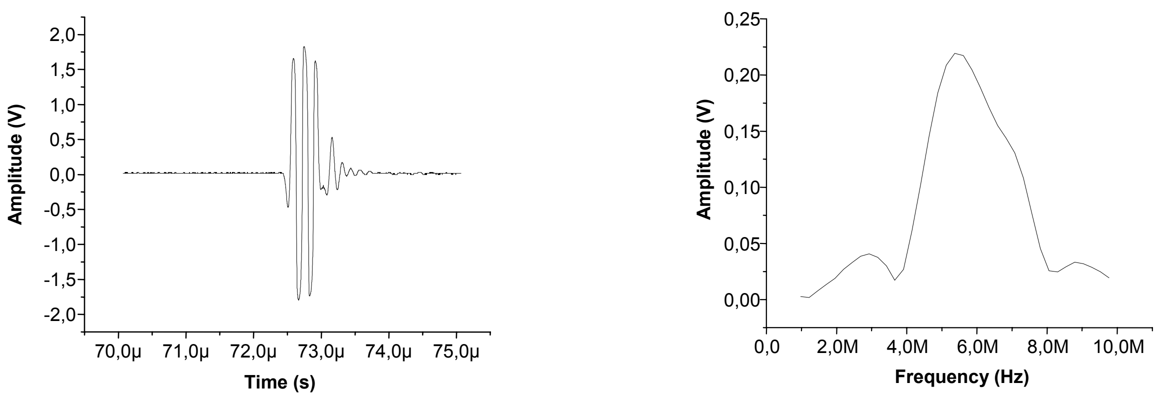
After the acquisition of values correspondent to the variation of the levels of the liquid surface, and the accomplishment of the calculation of void fraction for each flow parameter, it was verified that the obtained points present a tendency to linearity on relating bubbly flow (air flow) with void fraction. Thus, we have the average values of 0,645, 0,759, 0,891, 1,038 e 1,218% for void fraction when they are related to air flow of 0,4, 0,5, 0,6 e 0,7l/min respectively. Table 3 presents the relation between air flow and void fraction for the different parameters of the analyzed bubbly flows.

Table 3 Relation between air flow levels and void fraction for the different orifice sets

Air flow (l/min)	Void fraction (%)			
	Orifice set			
	045	055	07	08
0,4	0,605	0,650	0,665	0,660
0,5	0,760	0,755	0,765	0,755
0,6	0,950	0,875	0,875	0,865
0,7	1,120	1,040	0,975	1,015
0,8	1,295	1,295	1,145	1,135

6. Ultrasonic spectrum area

After the acquisition of the ultrasonic pulses reflected by the background wall of the column, these were treated and it was obtained the signal both in time domain and in frequency one. Figure 3 presents examples of this signal.



a) b)

Figure 3. Ultrasonic pulses, time domain (a) and frequency domain (b), referring to the orifice sets 045 with air flow of 0,6 l/min.

Analyzing the relation among the several calculated areas under the curve of the spectrum of ultrasonic frequency with the different orifice sets, for the different void fraction studied values; figure 4 was obtained, presenting the curve profiles and also table 4, which presents their respective values.

Table. 4 Values referring to calculated area under the ultrasonic spectrum curve (U.A.)

Orifice set	Void fraction (%)				
	0,645	0,759	0,891	1,038	1,218
0,45	750.354,94	741.134,30	715.822,04	674.597,53	638.657,72
0,55	122.307,86	100.654,48	75.104,93	90.623,34	90.577,25
0,70	80.059,45	138.997,65	219.057,15	237.689,15	247.869,95
0,80	234.124,38	297.714,81	318.854,74	351.752,88	478.754,93

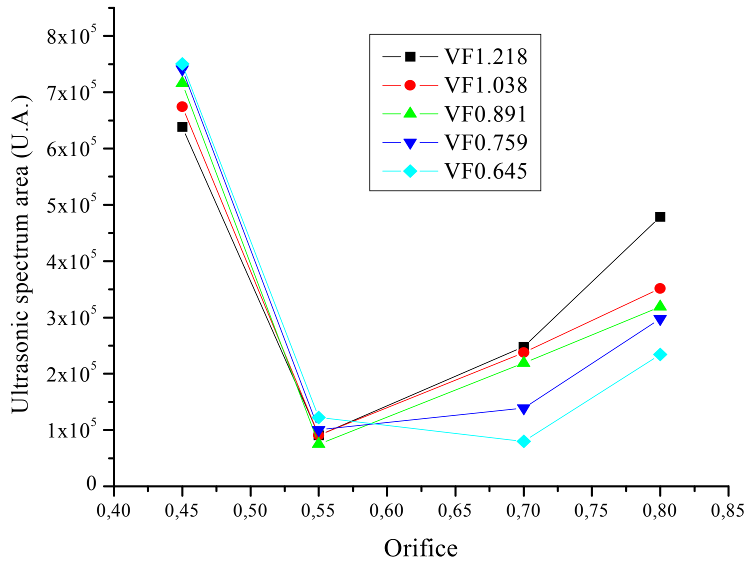


Figure 4. Ultrasonic spectrum area curves.

Observing figure 4, one verifies that to the orifice set type 045, the smallest signal (spectrum area) occurs according to the biggest void fraction, existing an inverse relation, between void fraction increase and the decrease of these signals. The orifice set type 055 presented the smallest signals, with the smallest absolute variation of the signals for the different void fractions. In the orifice set type 07, signal values presented the biggest percent variation (209%), Also, in this set, inversion occurs in relation to the spectrum area and void fraction, that is, differently from what occurred to the two first orifice sets, as void fraction increases, the area of the ultrasonic spectrum also increases.

To the orifice set type 08, inversion becomes sharp, opposing sharply to the behavior of orifice set type 045.

As increments in air flow are injected into the column, variations in the diameter and in bubbles quantity occur. Table 2 shows to a same orifice set, as increment occurs in air flow, it’s not verified either a definite increasing relation or a decrease of the diameter of the bubbles, but a balance tendency between variation of diameters and number of bubbles. As air flow increases, the total area of the transversal section of the bubbles, which is the product of the number of bubbles by transversal area of each bubble, also increases.

In the analysis of bubbly flow generated by the orifices 045 and 055, it was verified that the geometric shape of bubbles (spherical diameter and axes’ relation) and characteristics during the flow (bubbly density and total area of the transversal section) were similar, the same occurring among the bubbles generated by the orifices sets 07 and 08.

7. Conclusion

The geometric characterization of the bubbles, in the twenty different types of flow studied indicated that the bubbles generated by orifices 045 and 055 presented similar dimensions and geometric profiles, the same occurring to the bubbles generated by orifices 07 and 08.

Bubbles presented ellipsoidal profile with reason between main axes varying between 0,68 and 0,76. the bigger the internal diameter of the orifice set the more expanded the bubbles showed to be.

The orifice set 055 presented the nearest spectrum area values to the different void fractions analyzed, suggesting it to be the set that presents inflexion of behavior in direct (045 and 055) and inverse (07 and 08) relation of the spectral area with void fraction.

The ultrasonic pulse-echo technique, utilizing the frequency domain method, showed sensibility to the passing of bubble groups with average diameters. It also showed sensibility to the total variation of the transversal section of the bubbles (or interfacial area), as well as with the variation of void fraction.

By means of the analysis of the results it was possible to characterize bi-phase flows through a non-invasive technique, when they were compared with these flow parameters previously defined.

This work emphasizes the utilization of the ultrasonic frequency domain technique for bi-phase flows of the type air-water in the measurement of void fraction and detection of presence of bubbles; yet, a profound study is needed to verify its application in vertical cylindrical columns and in flows with bigger void fraction.

8. References

Chang, J. S. & Morala, E. C.; 1990, "Determination of two-phase interfacial areas by ultrasonic technique", Nuclear Engineering and design, v. 122, pp. 143-156.

Gonçalves, M. A. L.; 1991, *A aplicação de ultra-som na determinação de vazão em escoamento gás-líquido vertical*, Dissertação de M. Sc., UNICAMP, Campinas, SP.

Hofmann, B. & Rockstroh, M.; 1996 ,"Study on acoustic waveguides and reflectors for use in ultrasonic two-phase flow measurement", *Ultrasonics*, v. 34, pp. 431-434.

Hovart, D.; Mozina, J.; Zun, I., & Perpar, M.; 1998, "Laser ultrasonic for bubbly flow detection", Ultrasonics, v. 36, pp. 565-568.

Lamy, C.A.; Bittencourt, M. S. Q.; Faccini, J. L. H., Pio R. R., 1995; *Estudo preliminar de medição de vazão através de ondas ultra-sônicas*, IEN-68, Rio de Janeiro, RJ.

Liu, W. & Clark, N.; 1995, "Relationships between distributes of chord lengths and distributions of bubbles sizes including their statistical parameters", *International Journal Multiphase Flow*, v. 21, pp. 1073-1089.

Stravs, A.A.; Wahl, J.; Stockar, U. V., & Reilly, P. J.; 1987, "Development of an ultrasonic pulse reflection method for measuring relative size distributions of air bubbles in aqueous solutions", *Chemical Engineering Science*, v. 42, pp. 1677-1688.

Stravs, A. A.; Stockar, U. V.; 1985, "Measurement of interfacial areas in gas-liquid dispersions by ultrasonic pulse transmission" *Chemical engineering Science*, v. 40, pp. 1169-1175.

Sutin, A. M.; Yoon, S. W.; Kim, E. J., Didenkulov, N.; 1998, "Nonlinear acoustic method for bubble density measurements in water", *Journal Acoustic of Society America*, v. 103, pp. 2377-2384.

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