

PAPER • OPEN ACCESS

Liquid holdup optical measurements for horizontal stratified flows with an opaque fluid layer

To cite this article: I M Carraretto *et al* 2021 *J. Phys.: Conf. Ser.* **1868** 012030

View the [article online](#) for updates and enhancements.

You may also like

- [Effect of sodium hydroxide solution concentration on liquid entrainment in a steam boiler](#)

Piyatida Trinuruk, Somjate Meekaew, Ratchayothin Thong-in et al.

- [Behavior of Director Orientation near Interface of Nematic Liquid-Crystal Cell Evaluated Using Shear Horizontal Wave Propagation](#)

Hiroshi Moritake, Jaeki Kim, Katsumi Yoshino et al.

- [Phenomenological model for the prediction of the performance of a slurry bubble column reactor for green diesel production](#)

Y Muharam, A D Putri and A Hamzah



The Electrochemical Society

Advancing solid state & electrochemical science & technology

242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Abstract submission deadline: **April 8, 2022**

Connect. Engage. Champion. Empower. Accelerate.

MOVE SCIENCE FORWARD



Submit your abstract



Liquid holdup optical measurements for horizontal stratified flows with an opaque fluid layer

I M Carraretto¹, L P M Colombo¹, D Fasani¹ and M G Guilizzoni¹

¹Politecnico di Milano, via Lambruschini 4a, 20156 Milano (MI), IT

igormatteo.carraretto@polimi.it

Abstract. This study presents a method to measure the void fraction in presence of a stratified three-phase flow with an opaque fluid like foam. The commonly used resistive probes, which were successfully applied for air-water flows, fail in detecting the liquid/foam interface due to the variable conductivity of foam. To overcome this problem, a new optical method was developed. A probe consisting of a steel rod covered in red vinyl plastic with a black measuring scale having 1 mm resolution was introduced radially into the flow; the foam layer, being opaque, can be easily identified against the measuring scale in a side view of the flow. The behavior over time of the liquid-foam interface was thus recorded through a video camera. A couple of small LED lamps provided the lighting to record the scene. The videos were then processed to count the measuring scale marks below the foam layer in order to get the instantaneous values of liquid layer depth. Measurements were performed at different pipe sections. The results were compared to those obtained for air-water flows at the same superficial velocities, with the latter ranging from 0.76 to 2.30 m/s for air and 0.03 to 0.06 m/s for water respectively. A liquid loading reduction up to 41 % was detected at the lowest gas superficial velocity, i.e. 1 m/s, while when the gas superficial velocity increases the difference in the liquid holdup lowers and becomes negligible at 2.30 m/s, regardless the value of the liquid superficial velocity. Since no specific model exists for foamy flows, as a first attempt the Zuber and Findlay drift-flux model was finally adopted to correlate the data.

1. Introduction

In the study of multiphase flows, the distribution of the phases within the duct plays a fundamental role and it is usually taken into account in the models by means of quantities as the phase density function, void fraction and interfacial area concentration [1]. Sampling of such quantities is far from being an easy task and many techniques have been designed during the years, ranging from very complex and expensive ones (e.g. gamma-ray attenuation, high speed X-ray tomography, magnetic resonance imaging and wire mesh sensors, reference to some fundamental papers about these techniques



can be found in [2]) to much simpler devices as the different types of optical and electrical impedance probes which have been revised during the years ([3] – [9]).

In fact, in many multiphase flows, the phases have significantly different refraction indices and electrical impedances, and local or volume averaged measurement based on these quantities can reveal information about their spatial and temporal distribution within the flow. With a suitable selection of the probe geometry and appropriate calibration, such probes have been used to measure a variety of multiphase flow quantities, including film thickness in annular flows and liquid height in stratified flows (e.g. measuring the liquid layer depth by detection of the interface, thanks to a resistive probe in flush-wire configuration, as described in [9]). In fact, they can generate a practically “Boolean” voltage signal when the probe tip switch from a phase to the other, crossing the interface.

Between the two types, impedance probes are more robust and much less expensive, so they could seem the best solution for the experimental campaign object of this work. Regrettably, in presence of a foam layer above the liquid, they fail in detecting the liquid/foam “interface”, due to the non-uniform conductivity of the foam itself across its thickness that makes the voltage signal much more progressive between the phases and its thresholding arbitrary at the point of being not feasible. A new optical method was therefore developed, that exploits an optical approach but at cost much lower than commercially available local optical probes.

Such approach was applied to the study of air-water stratified flows in which surfactants were added to the liquid, so that a foam layer was created. Aim of the study was to evaluate the liquid holdup thickness reduction, in order to quantitatively evaluate the surfactants effectiveness in lowering the liquid loading in pipelines, as it might generate corrosion and gas dispatchment issues.

2. Experimental set-up and operating conditions

The experimental activity was carried out in the laboratory of Multiphase Thermal-Fluid Dynamics at the Department of Energy, Politecnico di Milano.

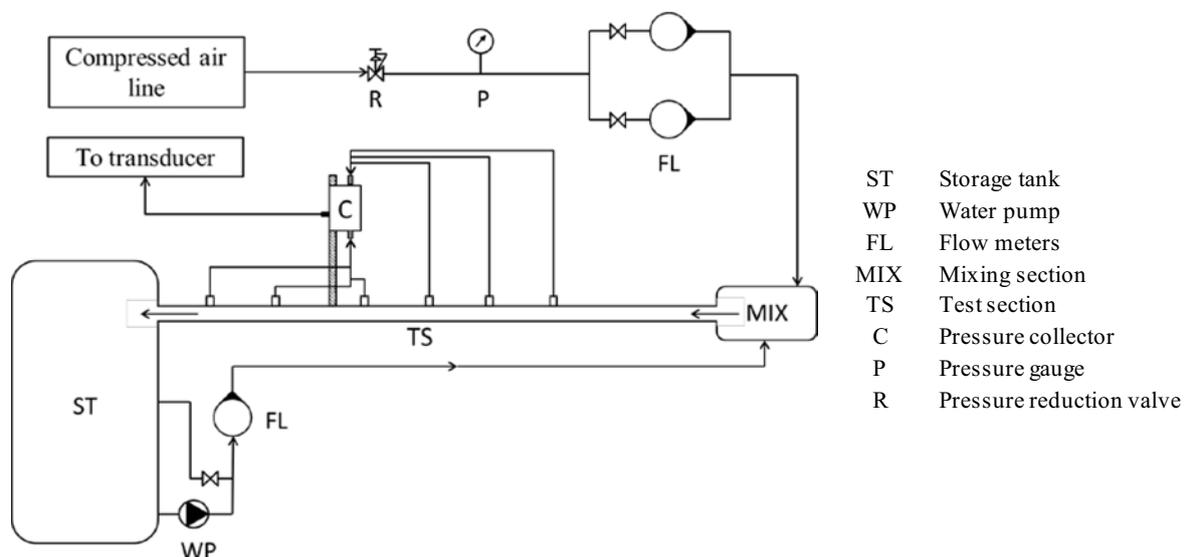


Figure 1. Experimental plant layout

The liquid is supplied from the bottom of a 4.0 m³ storage tank by means of a CALPEDA centrifugal pump (volume flow rate = 0.12 ÷ 0.75 m³/h; head = 6.5 ÷ 20 m). The liquid flow rate is measured by a float-type flow meter (whose characteristics are reported in Tab. 1) and set through a bypass valve upstream of the flow meter. Air flow rate is provided by the Department compressed air line at 0.8 MPa and measured by float-type flow meter, the reading of which is suitably corrected to account for pressure

and temperature deviation from standard conditions; the working point is set both through a pressure reducing valve and the flow meter valve. The liquid and the gas are injected into a mixing section, specifically designed to maximize the dispersion of one phase into the other to generate foam, if surfactants are present; subsequently the two-phase flow enters the test section of 60 mm inner diameter. More details about the setup, reported in Figure 1, can be found in [10] and in [11].

Table 1. Flow meters characteristics

Name	Fluid	Full Scale (FS)	Error	T _c [° C]	P _c [Pa]
ASAMETRO P13-2800	Water	0.1 ÷ 1 m ³ /h	± 3 % FS	20	-
ASAMETRO N5-2008	Air	2.5 ÷ 23.5 m ³ /h	± 2.5 % FS	20	101 325

The liquid loading, ε_{LL} , whether the foam was present or not, was evaluated by measuring the liquid layer depth h_L and by making use of equations (1) and (2), linking the geometrical quantities shown in Figure 2.

$$\varepsilon_{LL} = \frac{\Omega_{LL}}{\Omega} = \frac{\gamma - \sin\gamma}{2\pi} \quad (1)$$

$$\gamma = 2 \cos^{-1} \left(1 - \frac{h_L}{D} \right) \quad (2)$$

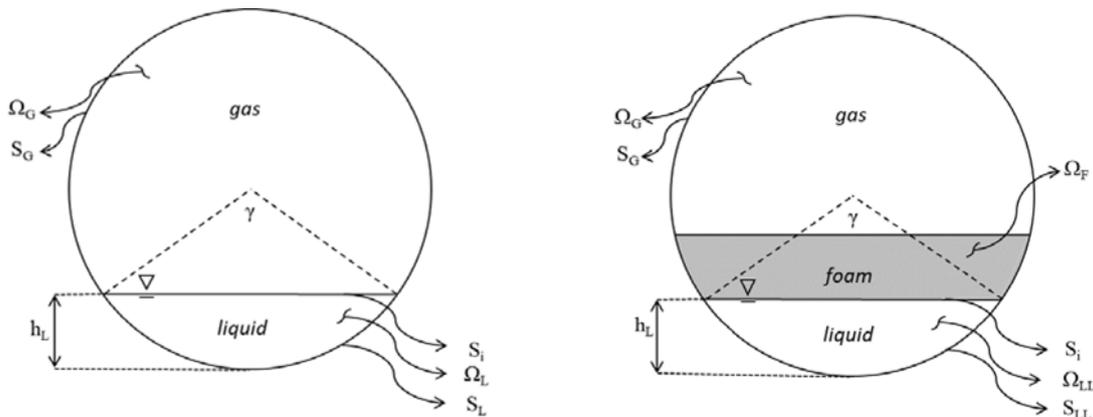


Figure 2. Sketch of the phase distribution in the pipe cross section with air/water (left) and air/water/foam (right)

In the case of air-water flow, ε_{LL} coincides with the liquid holdup $\varepsilon_L = \Omega_L/\Omega$, hence the void fraction is $\varepsilon = 1 - \varepsilon_{LL}$, Figure 2 (left).

In the presence of surfactants, the liquid content of foam must be considered. Since the cross-section area occupied by the foam Ω_F is not measured, its contribution, with reference to Figure 2 (right), is approximated considering that the cross-section area occupied by foam lies between zero (no foam) and $\Omega - \Omega_{LL}$ (foam that occupies the whole cross section free from the liquid). Void fraction is evaluated for $\Omega_F = 0$ (ε_{sup}) and for $\Omega_F = \Omega - \Omega_{LL}$ (ε_{inf}) and the average value is obtained, equation (3), with a relative error below 2 %, as the foam quality value is between 0.95 and 0.99.

$$\varepsilon \approx \frac{\varepsilon_{sup} + \varepsilon_{inf}}{2} = (1 - \varepsilon_{LL}) \frac{1 + FQ}{2} \quad RE_\varepsilon [\%] = \frac{(\varepsilon_{sup} - \varepsilon_{inf})/2}{\varepsilon} = \frac{1 - FQ}{1 + FQ} \quad (3)$$

In order to measure the liquid height, it was initially tested the use of resistive probes, which unfortunately resulted unable to provide a reasonable value, as the foam variable conductivity makes the output voltage signal vary too smoothly, and hence the liquid/foam interface too difficult to identify.

In reason of that, an optical technique was developed and implemented. The probe was introduced from above radially into the flow and it consists of a steel rod (2 mm in diameter) covered in red vinyl plastic with a black measuring scale having 1 mm resolution (Figure 3). The foam layer being opaque will itself indicate the liquid layer depth on the measuring scale.

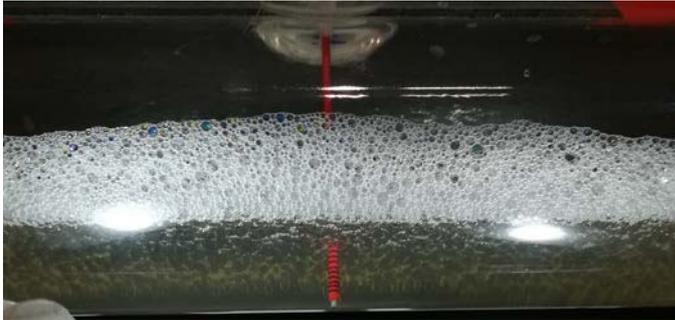


Figure 3. Optical probe immersed into the flow



Figure 4. Optical measurement equipment

The behavior over time of the liquid-foam interface was recorded through a video camera (JVC Everio GZ-EX215, 1080p, 25 fps) placed on a tripod; a couple of small LED lamps placed on a bracket bolted to the test section chassis provided the lighting of the recorded scene (Figure 4). Measurements were performed at two different locations to obtain an averaged value. The videos were processed and analyzed with a MATLAB® code, whose goal is to “read” the measuring scale, that is indeed to count the measuring scale marks left visible below the foam layer. For this purpose, the code implements the following functions from the Image Processing Toolbox:

1. Color Thresholding, which allows the selection and isolation of an image on a color basis, setting all the remaining portions to zero (black).
2. Image Binarization, which converts a grayscale image to a black and white image according to a threshold set by the user.
3. Region Analysis, which measures a set of properties for each connected component (region) in a binary image, displays this information in a table, and creates other binary images by filtering the original image on region properties.

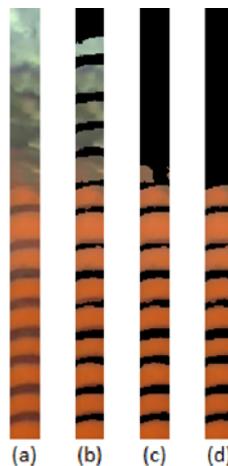


Figure 5. Procedure steps

With reference to Figure 5, for each video frame:

- (a) The code cuts a small region of each frame of the same width of the probe to eliminate background disturbances.
- (b) A “mask” is applied to each frame: it consists of a binary image superimposed on each frame in order to obtain a clear separation of the red areas. Such image is obtained from the frame characterized by the higher value of liquid depth in a single-phase flow (water), as it has the highest number of submerged (and therefore visible) marks.
- (c) Each frame is processed with Color Thresholding to isolate the red regions and delete the others.
- (d) The binary frames obtained from the previous step are processed with Image Region Analyzer, which filters the image regions by area and major axis length to delete small disturbances given, for example, by the light reflection on the bubbles.

After the described image processing steps, the code counts the number of regions left in each frame, corresponding to the instantaneous value of liquid layer depth, then it computes the average value over all the frames. As a further check of the reliability of the results, the code also creates a comparison video between the original unprocessed video (a), and its different stages of processing (b), (c) and (d), to visually check the correctness and quality of the analysis (and to identify and fix possible bugs during the development phase).

The implementation of this method does not require plant modifications, but it requires the presence of a continuous foam layer on top of the liquid layer, as in the case of a liquid-foam-air stratified flow pattern, since the code is not able to identify a transparent interface; this means that the method is unsuitable for measurements in plug flow regime. Furthermore, the results are influenced by the users' choice of some processing parameters, like color thresholds for image segmentation; to reduce the significance of such aspect, all the video processing was performed by two different operators.

Repeatability was checked by 3 repetitions for each of the two investigated pipe sections. The uncertainty on the single measure (intended as the average over the samples, being the camera frame rate and the acquisition time) is not known: in fact, despite the probe has known resolution (1 mm), nothing can be said about the error introduced by the video acquisition and processing steps, since it depends on many variables (lighting condition of the scene, probe positioning, camera positioning, video processing parameters) whose impact on the combined uncertainty is difficult to be evaluated.

Therefore, the uncertainty of the liquid depth measured at each pipe section (E_{h_L}) is evaluated by making use of the standard deviation of the repeated tests as it includes all the above-mentioned effects. The liquid loading ε_{LL} is a function of the liquid depth only, as shown in equation (1); its uncertainty is computed according to equation (4) and the uncertainty on the liquid height can be reasonably assumed within 0.5 mm [10], which is less than 5% of the liquid height itself considering the worst case scenario.

$$E_{\varepsilon_{LL}} = \left| \frac{d\varepsilon_{LL}}{dh_L} \right| E_{h_L} \quad \frac{d\varepsilon_{LL}}{dh_L} = \frac{d\varepsilon_{LL}}{d\gamma} \cdot \frac{d\gamma}{dh_L} = \frac{4/D}{\sqrt{1 - \left(1 - 2\frac{h_L}{D}\right)^2}} \cdot \frac{1 - \cos(\gamma)}{2\pi} \quad (4)$$

Moreover, uncertainties of the main quantities are reported in Tab. 2.

Table 2. Relative uncertainties of the main quantities

Quantity	J_G [m/s]	J_L [m/s]	ε_{LL} [-]	FQ [-]	ε [-]
Uncertainty [%]	2 ÷ 7	2 ÷ 3	1 ÷ 6	< 0.5	< 2

3. Results

Figure 6 reports the measured liquid holdup as a function of the gas superficial velocity, specifically the uncertainty on the superficial velocity coincide with the uncertainty on the volumetric flow rate as the ducts has a constant cross-section. Hence, according to equation (3) the void fraction value was

evaluated and compared to the reference case, i.e. air-water experiments analyzed in a previous study [10], as reported in Figure 7.

The void fraction variation is coherently positive at low gas superficial velocity J_G (+ 14 %) and becomes negligible or slightly negative at high J_G (− 4 %).

Such a behavior can be explained by the presence of a foam layer via two possible mechanisms, under the assumption, based on qualitative visual observation, that foam flows at an intermediate velocity between gas and liquid:

- The presence of foam forces the liquid to flow through a smaller section area and consequently (neglecting compression) at a higher velocity.

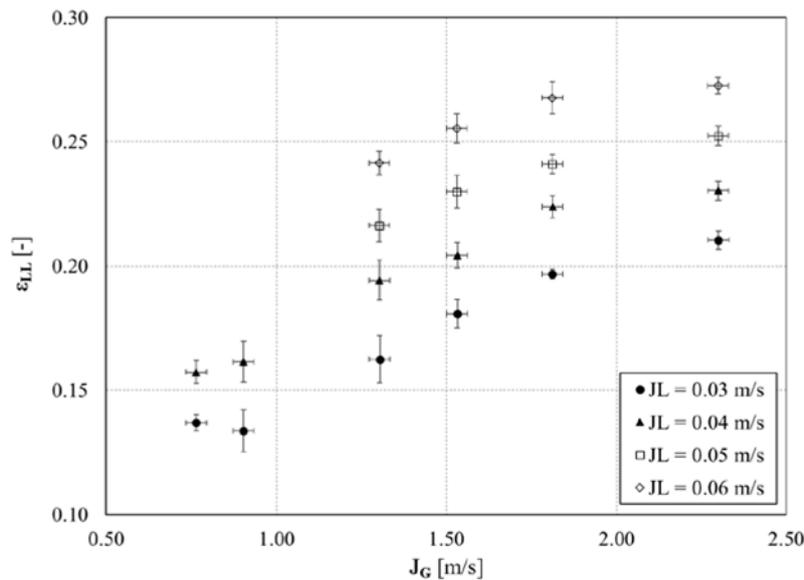


Figure 6. Liquid holdup vs. gas superficial velocity

- The liquid present in the foam flows at a higher velocity with respect to the underlying liquid layer, which means that, again neglecting density variations, it occupies a smaller portion of cross-section area compared to the one it would occupy if it was within the liquid layer;

As the foam layer becomes thinner, both effects disappear as reported in [11].

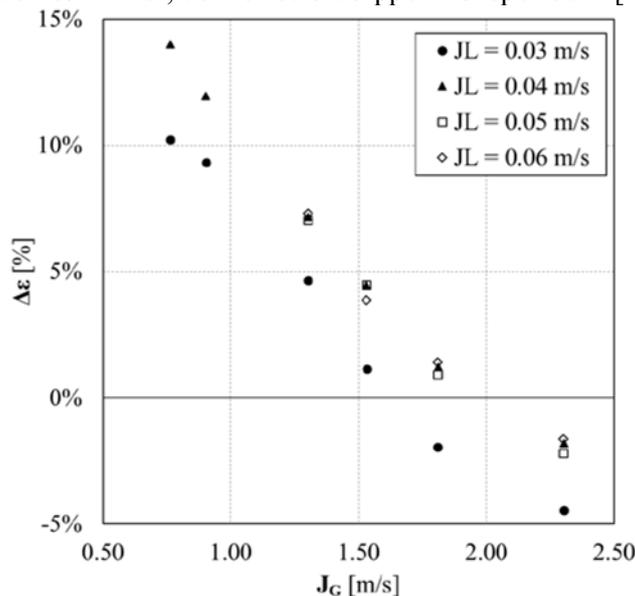


Figure 7. Void fraction percentage variation

Given the lack of specific models for foam flow, the behavior of void fraction was modelled with Zuber and Findlay drift-flux analysis, which is well known for being able to model void fraction of a two-phase flow regardless of the flow pattern.

Once void fraction is known, the actual gas phase velocity U_G can be computed and plotted against the mixture velocity J . Figure 8 shows in red the data, evidencing that they are indeed linearly correlated, and their linear fitting.

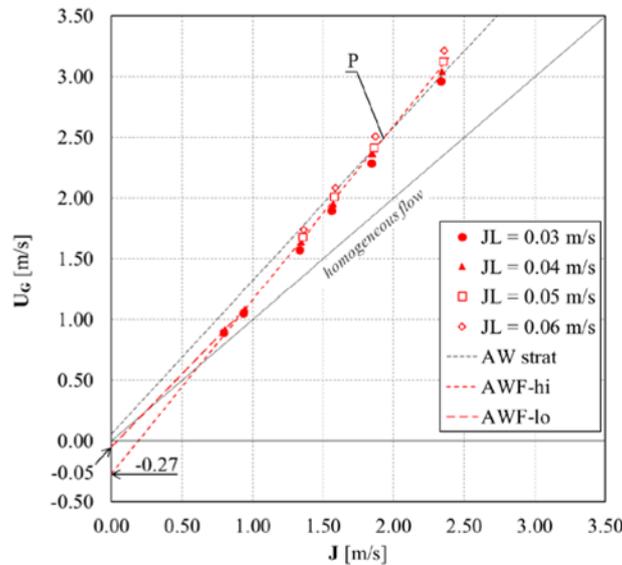


Figure 8. Zuber and Findlay analysis and comparison to air-water reference cases

It seems to appear from data observation that two different behaviors can be identified, according to the gas superficial velocity:

- For $0.76 < J_G$ [m/s] < 0.90 and J_L [m/s] = 0.03 and 0.04, the fitting parameters are $C_0 = 1.20$ and $U_{G,j} = -0.05$ m/s, regardless of the liquid superficial velocity;
- For $0.90 < J_G$ [m/s] < 2.3 , the experimental data line up in different series according to the liquid superficial velocity: $U_{G,j}$ is independent of J_L and equal to -0.27 , while C_0 appears to be a linear function of J_L with a mean value of 1.43, cf. equation (5). The model fits data with a mean absolute percentage error (MAPE) below 0.8 %.

$$\varepsilon = \frac{x_v J}{1.20J - 0.05} \quad (i) \quad \varepsilon = \frac{x_v J}{C_0 J - 0.27} \quad (ii) \quad \text{where} \quad C_0 = 3.11J_L + 1.29 \quad (5)$$

Further investigation is required to clarify and confirm the reported observations.

As a comparison, the plot also shows the results of the same analysis on the air-water flow (black dashed line), for $C_0 = 1.26$ and $U_{G,j} = 0.06$ m/s, cf. equation (6), for a more detailed description of the analysis please refer to [10].

$$\varepsilon = \frac{x_v J}{1.26J + 0.06} \quad (6)$$

The average drift velocity of the air-liquid-foam is in both cases negative: this is not uncommon in two-phase horizontal flow with phase separation. With reference to equation (7), where ε^* is the *local* void fraction, this implies that there are regions of the pipe cross section where the local gas velocity is lower than the local mixture flux density ($U_G < J$). This region must be in the foam layer boundaries,

i.e. at liquid/foam interface, since in the liquid layer the local void fraction ε^* is zero, in the gas free region $u_G \equiv j$, and the foam layer behaves as a homogeneous phase.

$$U_{G,j} = \frac{\overline{U_{G,j}\varepsilon^*}}{\varepsilon} = \frac{\frac{1}{\Omega} \int_{\Omega} (u_G - j)\varepsilon^* d\Omega}{\frac{1}{\Omega} \int_{\Omega} \varepsilon^* d\Omega} \quad (7)$$

4. Conclusions

The determination of the liquid holdup in presence of an opaque fluid layer was performed developing a new technique, which resulted to be very promising in overcoming the issues related to the use of resistive probes in these situations. The method developed and here presented is considerably cheaper if compared to the commonly adopted foam capacitance probes and it appears reliable too, having an uncertainty on the measured liquid holdup lower than 10%. Eventually, the obtained results were modelled using the Zuber and Findlay model and then compared to the air-water reference case, showing that the beneficial effect of surfactants injection tends to reduce as the superficial gas velocity increases. Experimental campaigns including comparison between other measuring procedures (e.g. based on image processing of side views of the duct) and the proposed one is being planned for further validation of the results. Furthermore, a more advanced technique, based on a three colors probe, is under development, and the obtained results are going to be compared with the present ones.

References

- [1] Ishii M and Hibiki T, 2011, “Thermo-fluid dynamics of two phase flow”, Springer-Verlag New York
- [2] Guilizzoni M, 2013, “Flow pattern identification in gas-liquid flows by means of phase density imaging”, *International Journal of Multiphase Flow*, 51, 1 – 10
- [3] Bergles A E, 1969, “Electrical Probes for the Study of Two-Phase Flows”, *Proceedings of the Eleventh National ASME/AIChE Heat Transfer Conference*, Minneapolis, 70 – 81
- [4] Jones O C and Delhaye J, 1976, “Transient and Statistical Measurement Techniques for Two-Phase Flows: A Critical Review”, *International Journal of Multiphase Flow*, Vol, 3, 89 – 116
- [5] Hewitt G F, 1978, “Measurement of Two Phase Flow Parameters”, Academic Press, London, 57 – 60
- [6] Banerjee S and Lahey R T Jr, 1984, “Advances in Two-Phase Flow Instrumentation, Advances in Nuclear Science and Technology”, Lewins, J., and Becker, M., eds.. Plenum Press, New York, Vol. 13, 227 – 414
- [7] Cheremisinoff N P, 1986, “Instrumentation for Complex Fluid Flows”, Technomic Publishing Inc, Lancaster, PA, 73 – 103
- [8] Jones O C, Lin J T and Ovacik L, 1992, “Investigation of Electrical Impedance Imaging Relative to Two-Phase, Gas-Liquid Flows”, *Chemical Engineering Communications*, Vol. 118, 299 – 325
- [9] Ceccio S L and George D L, 1996, “A review fo electrical impedance techniques for the measurement of multiphase flows”, *Journal of Fluids Engineering*, vol. 118, 391 – 399
- [10] Carraretto I M, Colombo L P M, Fasani D, Guilizzoni M and Lucchini A, 2020, “Pressure drop and void fraction in horizontal air-water stratified flows with smooth interface at atmospheric pressure”, *Fluids*, 5, 101.
- [11] Colombo L P M, Carraretto I M, Di Lullo A G, Passucci C and Allegrucci A, 2018, “Experimental study of aqueous foam generation and transport in a horizontal pipe for deliquification purposes”, *Experimental Thermal and Fluid Science*, 98, 369 – 380
- [12] Hand N. P., Spedding P. L. and Ralph S. J., 1992, “The effect of surface tension on flow pattern, holdup and pressure drop during horizontal air-water pipe flow at atmospheric conditions”, *The Chemical Engineering Journal*, 48, 197 – 210.