Horizontal air-water flow pattern recognition

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Abstract

A Wire Mesh Sensor (WMS), based on the measurement of the local instantaneous conductivity of the two-phase mixture, has been adopted to characterize the air-water flow in a test section consisting of a horizontal Plexiglas (transparent) pipe of internal diameter 19.5 mm and total length of about 6 m. The flow quality ranges from 0 to 0.73 and the superficial velocity ranges from 0.145 to 31.94 m/s for air and from 0.019 to 2.62 m/s for water; the pressure ranges from atmospheric pressure to 3.7 bar. The observed flow patterns are stratified-bubble-slug/plug-annular. The void fraction profiles are derived from the sensor signals and their evolution in time and space is analyzed and discussed; the dependence of the signals from the measured fluid dynamic quantities is discussed too.
Keywords : horizontal two-phase flow, flow pattern, void fraction profiles.

1 Introduction

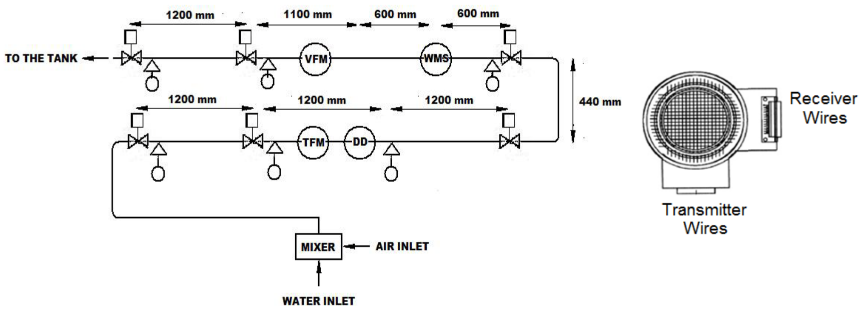
In a gas-liquid horizontal pipe flow the flow pattern is the result of a mechanical and thermal dynamic equilibrium between the phases and depend on a large number of important parameters: the phases superficial velocity, pressure and temperature, the fluid properties (density, viscosity, surface tension) and the channel geometry. Numerous theoretical and experimental works, about the horizontal flow, have been performed by several authors (Hewitt and Hall-Taylor [1], Taitel and Duckler [2], Andreussi and Bendiksen [3]), but the problem concerning the characterization of the flow structure (void fraction profiles and interface) is still open. A comprehensive classification of flow regimes in different pipe configuration and operating conditions is given by Rouhani and Sohal [4] and Thome [5]. Generally, the flow recognition is made by visual observation or by using flow pattern maps (Baker [6] and Mandhane *et al.* [7] for example); when the direct visualization is unavailable other techniques

WIT Transactions on Engineering Sciences, Vol 79,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/MPF130381

have to be used: optical techniques, nuclear radiation attenuation, impedance electrical techniques. Available methodologies for the flow pattern recognition are the analysis of the static pressure fluctuation probability density function (PDF) [8], the cross-correlation analysis [9] of two pressure transducers or the statistical analysis of the density function time series [10]. A straight approach used to characterize the flow, is based on the measurement of the local as well as of the cross-section or volumetric average void fraction values. The void fraction can be measured by means of several techniques, including radiation attenuation (*X* or γ-ray or neutron beams) for line or area average values (Jones and Zuber [11]), optical (Bertola [12]) or electrical contact probes (Prasser *et al.* [13]) for local values, impedance techniques by using capacitance or conductance sensors and quick-closing valves based on the phases volume measurement. Wire Mesh Sensors (WMS), based on the measurement of the local instantaneous conductivity of the two-phase mixture, are used for the evaluation of void fraction profiles, bubble size distributions and gas velocity distributions and for a high-speed visualization of a gas–liquid flow. The WMS has been used, in different geometry and for different configurations, to study the cross-section average void fraction and the gas profile evolution (Prasser *et al.* [13, 14]). Comparative measurements between WMS and an X-ray tomography technique have shown that the accuracy of the cross-section average void fraction depends on the two-phase flow pattern. Differences in the absolute void fraction were determined by Prasser *et al.* [15] for bubble flows in the range of ± 1%, while a systematic underestimation of approximately - 4% was observed for slug flows. Da Silva *et al.* [16] have developed a WMS system based on permittivity (capacitance) measurements, which has been applied to investigate multiphase flows involving non-conducting fluids, so extending the application of WMS to new application fields. In the present work a WMS has been adopted to characterize the air-water two-phase flow in a horizontal Plexiglas tube (D_i=19.5 mm): local, chordal, cross-section void fraction values are derived from the sensor data and the flow evolution in time and space is analyzed and discussed. The dependence of the signals from the measured fluid dynamic quantities is discussed too. The main task is to estimate which flow pattern will exist under any set of test conditions, as well as to predict the value of characteristic fluid and flow parameters from the analysis of the void fraction chordal profiles that are extracted from the WMS signal time history.

1 Experimental facility and instrumentation

The experimental facility consists of the feed water loop (tap water with conductivity of about 620 μS is used), the feed air loop and the test section. The liquid flow rate higher than 900 l/h is measured by means of an electromagnetic flow meter in a range of 0.9-36 m^3/h with a ±0.5% r.v. accuracy value. The lower water flow rates are measured by means of a rotameter in the ranges of 0-100 l/h and 100–400 l/h. The air flow rate is measured at the inlet of the test section by means of different rotameters for the different ranges: 6300–63000 Nl/h, 500–5000 Nl/h and 50–300 Nl/h, with a ±2% f.s.v. accuracy value. A pressure gauge near the flow meter allows the correction of flow meter readings. The test section (figure 1 (a)) consists of a 19.5 mm diameter and about 6 m long horizontal pipe; two straight sections of the whole pipe having lengths of 4000 m and 2000 m respectively are connected by means of a 90° horizontal elbow. The WMS is installed in the second section of the facility between two Plexiglas pipes having a length of 600 mm each. The test section is equipped with quick closing valves to measure the volumetric void fraction in a length of 1200 mm, and with several pressure transducers for absolute and differential pressure measurements. Experiments have been performed at water temperature of about 20°C. At the inlet of the test section the pressure is measured by means of an absolute pressure transducer. The acquisition data from the other instruments, that are installed in the test section (Venturi Flow Meter, Drag, Disk, Turbine Flow Meter), are not discussed in the present paper. The present work concerns the behavior of the WMS, made by Teletronic Rossendorf GmbH [17]: the WMS sensor working principle is the measurement of the conductivity of the fluid. As air and water have different electrical properties (water is high conductive while air is a good insulator) the measurement of the conductance can be analyzed to detect the presence of each phase inside the pipe. The WMS (figure 1 (b)) consists of two planes of parallel wire grids (16x16) that are placed across the channel at a short distance from each other (1.5 mm) and span over the measuring cross section; the wires of both planes cross under an angle of 90°. The sensor has been designed to cover the cross section of a pipe having an internal diameter equal to 19.5 mm: the wires diameter D_{wire} is 70 μm and the pitch p is 1.3 mm, so that only the 5.4% of the pipe section is occupied by the sensor. The measuring grid allows us to obtain a spatial resolution of the order of the pitch (1.3 mm) and, due to the high time resolution (up to 10.000 frames/s), the evolution of the local void fraction as a function of the local electrical conductivity can be analyzed.



(a) (b)

Figure 1: Test section (a) and sensor 16x16 WMS200 (b).

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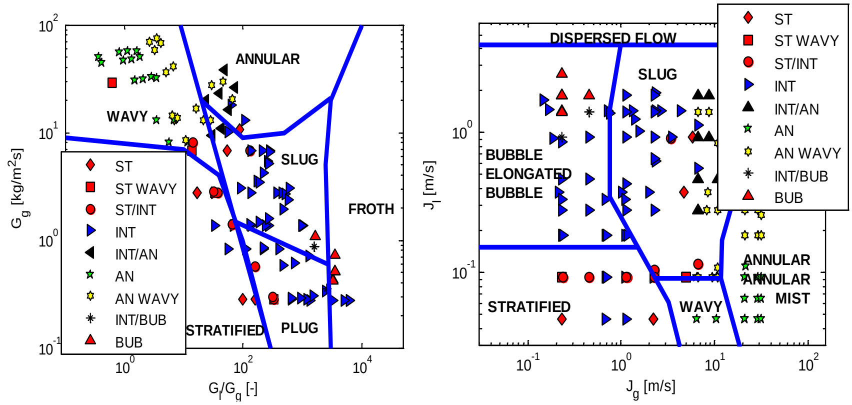
2 Horizontal flow pattern characterization and experimental matrix

One of the main features of horizontal pipe flow compared to vertical and inclined flows is the tendency to the flow stratification. The gas phase tends to migrate towards the upper part of the channel while the liquid flows rather in the lower part of the channel owing to density difference, regardless of the flow pattern. In horizontal gas-liquid flow the flow can be classified in four general flow patterns: stratified flow, bubble flow, slug/plug flow and annular flow. Each flow pattern can be also divided in sub-categories: stratified flow in smooth and wavy flow, intermittent flow in slug and plug flow and annular flow in smooth, wavy and mist flow. In the present tests, the liquid flow rate W_l ranges from 0.0056 kg/s to 0.78 kg/s while the air flow rate W_g ranges from 0.083 g/s to 22.5 g/s; the flow quality ranges from 0 to 0.73 and the superficial velocity ranges from 0.15 to 31.94 m/s for air and from 0.019 to 2.62 m/s for water; the pressure ranges from atmospheric pressure to 3.7 bar. The comparison between the observed flow patterns and the prediction by the Baker's and the Mandhane's maps is reported in figure 2. The test flows are identified by the phases mass fluxes ($G_g = W_g/A$, $G_l = W_l/A$, where A is the pipe cross section) and superficial velocities (J_g, J_l).



(a) (b)

Figure 2: Comparison between Baker's Map (a) and Mandhane's Map (b) flow patterns prediction and present observations. Legend: ST=Stratified, INT=Intermittent, AN=Annular, BUB=Bubble.

3 Signal processing

The WMS sensor signals are acquired by means of WMS200 electronics and processed in Matlab® environment. The output is a 3-D matrix *V(i,j,k)*, where the indexes *i* and *j* are related with the space position of the mesh points and *k* is the time index. The value of *V(i,j,k)* is a digital signal proportional to the local fluid conductivity. The indexes i and j refer to transmitting wires and to receiving wires respectively. In order to analyze the signals, the location of the wires respect to the pipe is defined: the points of the grid, that are located near the wall, are analyzed taking into account the wall influence, while the points, that are located outside the cross section of the pipe, are excluded from the analysis. The developed signal processing scheme is structured to obtain the desired two-phase flow parameters. First of all the signal is normalized taken into account the single phase reference matrix. The normalized time history signal of each mesh point is calculated as

$$V^*(i,j,k)=\frac{V(i,j,k)-V_w(i,j)}{V_a(i,j)-V_w(i,j)} \tag{1}$$

where V_w and V_a are the time averaged values of the signals with the pipe filled with water or air at the beginning of the test.

The signal normalization can be considered as an approximation of the local void fraction value, if a linear relationship between conductivity and void fraction and a reference area equal to the square of the wire pitch p (Prasser *et al.* [14]) are assumed. The local void fraction value is evaluated taking into account the position of the measuring point by using a matrix of geometrical weights, $a(i,j)$.

A fundamental task for the flow analyses is then the choice of the signal acquisition frequency and of the observation time. A high acquisition frequency allows the detection of fast phenomena while a long observation time allows us to detect slow phenomena. In the present work we focus the attention on the macroscopic flow objects (plug, slug, bubbles, droplets, waves, etc.) having a length L_o, that propagate along the pipe with a velocity v_o, and with a sensor observation time $\tau_o=L_o/v_o$.

At the first step, the local time series void fraction at each measuring point (i,j) is analyzed by means of normalized histograms.

The local instantaneous void fraction α has been obtained with an acquisition frequency f_{acq} equal to 1250 Hz for a total observation time T_T equal to 20 s, so that the value of k ranges from 1 to k_T, where k_T is the total number of measured frames, that can be expressed by the eq.

$$k_T = f_{acq} \cdot T_T \tag{2}$$

and the corresponding time is

$$t = k \cdot \frac{T_T}{k_t} \tag{3}$$

The selected acquisition frequency (1250 Hz) is sufficient to detect and characterize objects having a minimum space length equal to

$$L_{\min} = \frac{2u_{\max}}{f_{acq}} \tag{4}$$

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As the flow velocity *u* ranges from 0.26 m/s to 32 m/s, the minimum length at lower velocity is of the order of 0.5 mm, while at higher velocity is of the order of 50 mm. In the present study, the flow is characterized in terms of macroscopic phenomena, that can be considered as deterministic ones, while the microscopic phenomena are considered as stochastic phenomena and are evaluated by means of a statistical analysis. The selected observation period (20 s) allows the analysis of phenomena having a characteristic frequency higher than 0.1 Hz.
In order to analyze the fast phenomena in terms of average values, a moving average of the local void fraction time values has been performed, on the basis of a time interval $\tau < T_T$ and $\tau > 2/f_{acq}$,by the eq.

$$< \alpha(i,j,t,\tau) >= \frac{1}{\Delta t}\int_{t-\frac{\tau}{2}}^{t+\frac{\tau}{2}} \alpha(i,j,t)dt = \frac{1}{\Delta k}\sum_{l-\frac{\Delta k}{2}}^{l+\frac{\Delta k}{2}} \alpha(i,j,l) =< \alpha(i,j,k,\Delta k) > \tag{5}$$

where

$$l = \Delta k/2, \ldots., \mathrm{k_T} - \Delta k/2$$

$$\Delta k = f_{acq} \cdot \tau$$

Every time averaged local void fraction has been characterized from the statistical point of view by means of the root mean square defined by the following equation

$$\sigma_a(i,j,t,\tau) = \sigma_a(i,j,k,\Delta k) = \left[\frac{1}{\Delta k} \cdot \sum_{l-\Delta k/2}^{l+\Delta k/2} \left(\alpha(i,j,l) - < \alpha(i,j,k,\Delta k) >\right)^2\right]^{1/2} \tag{6}$$

In order to characterize the flow the chords have to be selected depending on the flow structure itself. According to the observed flow patterns, 3 fundamental chords are considered, in the vertical direction; the chords are used to evaluate the flow structure in the pipe center line and the symmetry of the flow structure with respect to the center, as well as the curvature effects.

The variation in time of the chordal profile has been analyzed considering the parameter defined as

$$M(t) = \sum_{i=1}^{16} \left(< \alpha(i,j,t,\tau) > - < \alpha(i,j,t-\tau,\tau) >\right) \tag{7}$$

4 Experimental results

4.1 Histograms local analysis

The histograms are obtained by using a number of groups given by the Kendal-Stuart [17] grouping guide and give information about the probability density function (PDF) of the local void fraction.

The analysis of the normalized histograms, that are evaluated for each measuring point and for the total observation time, allows us to define if a deterministic or a stochastic behavior characterizes the flow.

In figure 3 the normalized histograms along the central chord (*j*=8) are shown at three different flow velocities. The ratio J_g/J_l is $9{\cdot}10^2$, 1.18 and 122 for the case (a), (b) and (c) respectively. Depending on the phases velocity combination, the flow assumes a stochastic behavior (figure 3 (a-c)) or a deterministic behavior (figure 3 (b)). In table 1 the corresponding local mean void fraction values and the parameter σ/α_{mean}, where σ is the standard deviation of the signal and α_{mean} is the average void fraction, are shown; the parameter σ/α_{mean} is an index of the fluctuation of the signal. If a stochastic behavior is observed the mean value of the void fraction can be considered as representative of the flow, while in case of deterministic behavior further analysis is required.

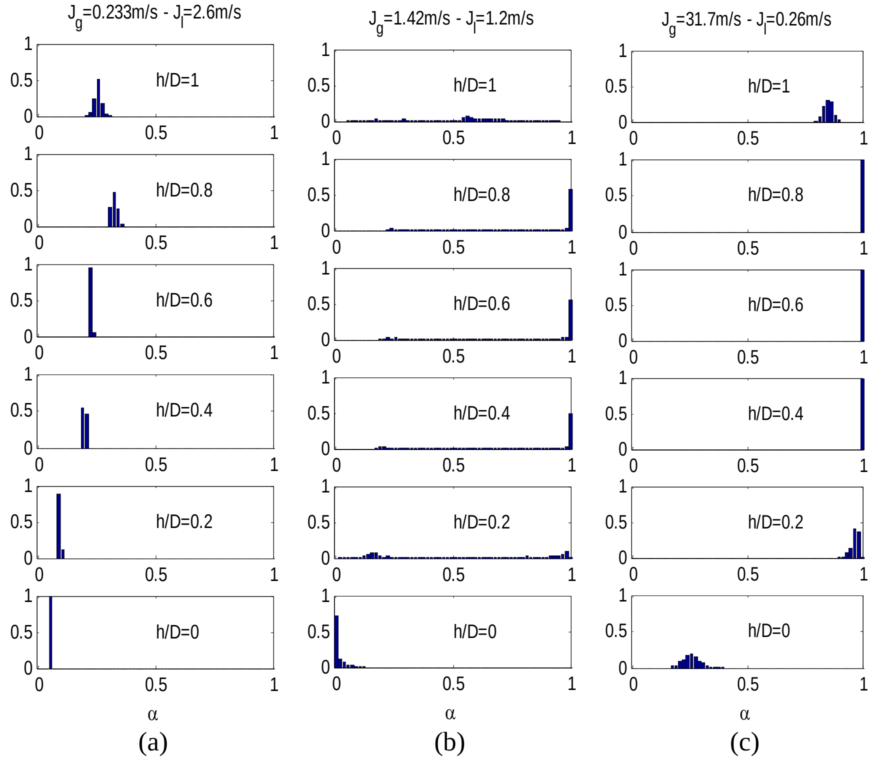


Figure 3: Normalized histograms along *j*=8 at different flow velocities.

If the standard deviation value of the local void fraction is low and the PDF is a Gaussian, the flow can be characterized with a well defined void fraction profile. If the PDF is not a Gaussian, and a quasi periodic behavior can be defined for the macroscopic structures of the flow, the characteristic times and the characteristic profiles have to be extracted.

Table 1: Local average void fraction and standard deviation values along *j*=8 at different flow velocities.

	(a)		(b)		(c)	
	J_g = 0.23 m/s- J_l = 2.6 m/s		J_g = 1.42 m/s- J_l = 1.2 m/s		J_g = 31.7m/s - J_l = 0.26 m/s	
h/D	α_{mean}	σ/α_{mean}	α_{mean}	σ/α_{mean}	α_{mean}	σ/α_{mean}
0	0.051	0.02	0.0126	1.76	0.256	0.156
0.2	0.089	0.043	0.535	0.643	0.966	0.016
0.4	0.195	0.024	0.766	0.391	0.997	0.001
0.6	0.224	0.011	0.804	0.353	0.999	0.0002
0.8	0.322	0.038	0.819	0.318	0.998	0
1	0.252	0.057	0.524	0.455	0.851	0.023

4.2 Void fraction chordal profile analysis

The analysis of the moving average of the local void fraction values is performed and the profile time evolution is analyzed by means of the parameter *M(t)*, defined in section 4. If the value of *M(t)* is zero or lower than 0.1 the void fraction profile is classified as “non periodic with low noise”. Starting from the evolution in time of *M(t)* it is possible to define the time intervals in which the profile is not changing and the time interval where is changing. The chordal profiles for the selected time points are then analyzed and used to characterize the flow pattern in terms of time evolution, characteristic shape and parameters.
In figure 4 the time evolution of the parameter *M(t)* is shown for different superficial velocities of air and water.

The optimum time interval, used for the moving average, has been selected as the minimum averaging time, that allows us to maximize the time period in which *M(t)* is zero. The history of the parameter *M(t)* is strongly dependent on the superficial velocities in both frequency and amplitude; the amplitude is relatively low for the flows characterized by a high value of the superficial velocity of one phase in combination with a low value of the velocity of the other phase, while it increases when the two phases velocities approach each other. Moreover the noise level of *M(t)* increases by increasing the water velocity for all the tested conditions and on such basis it is possible to extract the profiles that characterize the flow at different time period: if the amplitude is lower than a threshold value the flow can be characterized by means of the average profile and the correspondent standard deviation, while for higher amplitudes (*M(t)* higher than 0.1 in absolute value) a number of profiles depending on the time history have to be analyzed. In this case the flow evolution can be divided in two categories “quasi periodic profile” and “non periodic profile with high noise”: the profile is classified as “quasi periodic” if there is a time period in which the profile doesn’t change significantly (*M(t)* value near zero), while it is classified as “non periodic high noise” if the absolute value of *M(t)* is higher than zero and the local flow is characterized by a chaotic behavior. For the “high noise” profile, in which the value of *M(t)* is continuously changing, the time evolution is characterized by means of the average profile, that is evaluated adopting the observation time of 20 s, and by means of the relative standard deviation. For the “quasi periodic” profile at least two characteristic profiles with the related time are extracted considering the time periods in which *M(t)* is near zero and the time periods in which the flow is evolving and *M(t)* is higher than zero.

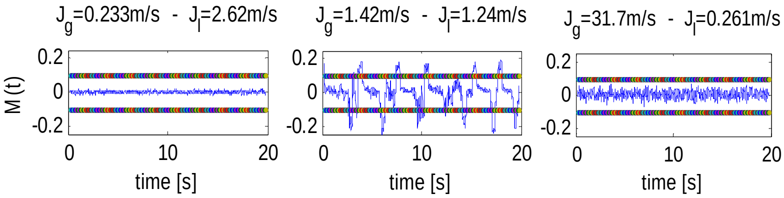
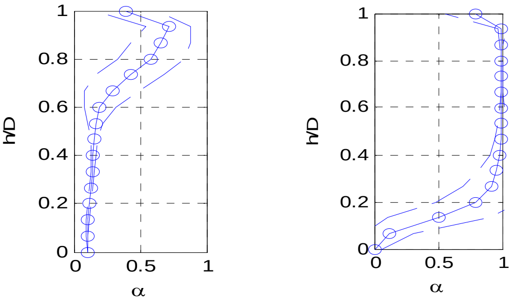


Figure 4: *M(t)* at *j=8* for different superficial velocities.

If the water superficial velocity (J_l) is lower than 0.5 m/s and the air superficial velocity (J_g) is lower than 10 m/s the profile evolution is characterized by a low noise level; if the air velocity is increased at values higher than 10 m/s, keeping the water velocity at values lower than 0.5 m/s, the amplitudes related to the profile change evolution parameter are lower than the threshold value and then the flow can be characterized by means of a single profile shape. If the value of the air velocity is lower than 10 m/s and the water velocity is higher than 0.5 m/s the evolution of the *M(t)* is characterized by a high noise and by an amplitude higher than the threshold value; but if the water velocity increases the amplitude tends to decrease and an amplitude lower than 0.1 has been detected for the flow characterized by a water superficial velocity higher than 1.4 m/s and an air superficial velocity lower than 0.5 m/s.

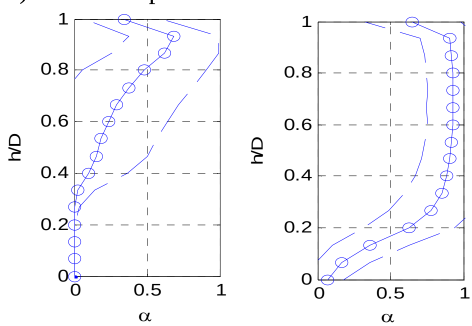
Every air-water flow classified as “non periodic with low noise” is characterized by the average profile that does not depend on the observation time, and on the related standard deviation at each measuring point along the chord. In this group two different shapes of void fraction profiles can be distinguished for bubble flow and annular/stratified flow patterns. The annular/stratified flow occurs at high air superficial velocity (higher than 4 m/s and up to 32 m/s) and low water velocity (J_l ranges between 0.05 and 0.28 m/s). Moreover if the value of J_l is lower than 0.1 m/s the liquid film region in the upper wall (h/D=1) is not observed by the sensor; by increasing the water flow rate the presence of the liquid phase is instead detected in the upper region. In the core region the void fraction assumes a value close to one. The characteristic profiles for bubble flow are instead obtained at higher water velocities (J_l higher than 1.8 m/s) and lower air velocities (J_g ranges between 0.23 and 0.46 m/s). In figure 5, the characteristic void fraction chordal profiles are shown for two different flows, together with (α_{mean} $\pm\sigma$) values that are plotted as dashed lines; the typical profile of an horizontal bubble flow is shown in figure 5(a), while in figure 5(b) the flow can be classified as annular.



(a) (b)

Figure 5: Void fraction chordal profiles for "non periodic with low noise" profile flows. (a): J_g=0.23 m/s – J_l=1.86 m/s; (b): J_g=8.34 m/s – J_l=0.28 m/s.

If the flow is classified as "non periodic with high noise", as in figure 6, the void fraction profile is characterized in terms of average values and standard deviations. Also in this case it is possible to identify two different shapes of the void fraction chordal profiles depending on the phases' velocity. If the value of J_l is higher than 0.93 m/s and J_g ranges between 0.14 and 2.32 m/s the void fraction along the central chord assumes the typical shape that is reported in figure 6(a), while, if the flow air velocity is higher than 2 m/s and the liquid velocity ranges from 0.63 to 1.86 m/s the void profile assumes the shape reported in figure 6(b). The flow is characterized by a mean void fraction in the core region that is lower than one and by a higher thickness of the liquid film in the upper region, compared to the annular flow classified as "non periodic with low noise". In figure 6 the (α_{mean} $\pm\sigma$) values are plotted as dashed lines.



(a) (b)

Figure 6: Characteristic void fraction chordal profile for "high noise" flows at (a): J_g=0.17 m/s – J_l=1.46 m/s; (b): J_g=6.66 m/s – J_l=0.93 m/s.

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If the flow is classified as “quasi periodic”, as for the figure 7 cases, the characteristic profiles concerning the different periods are extracted and analyzed in terms of shape, characteristic time and PDF. This type of flow is then described at least by two characteristic profiles and by the characteristic time of each one, figure 7(a) and (b). This type of flow is typical of intermittent flows, such as slug flow. The red line (circles) refers to the slug region profile, while the blue line (diamonds) refers to the bubble region profile of the slug unit; the dashed lines represent the (α_{mean} ±σ) profile; the total slug and bubble residence time is also shown.

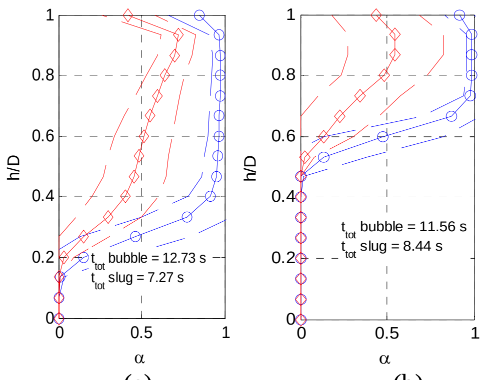

Figure 7: Void fraction chordal profile for the “quasi periodic” flows at (a): J_l=0.43 m/s and J_g=1.14 m/s and (b): J_l=0.19 m/s and J_g=0.24 m/s.

5 Conclusions

A methodology for the flow pattern recognition and for the quantitative characterization of the air/water horizontal flow has been developed, on the basis of the Wire Mesh Sensor signal analysis. For all the observed flows pattern the characteristic void fraction profiles and their time evolution are extracted from the sensor data in order to investigate the internal structure of the flow. The dependency of the signals from the measured fluid dynamic quantities has been discussed. Further analyses are required to define the pressure effects on the void fraction profile shape.

Acknowledgements

The present research has been supported by ENEA and by the Ministry of Economic Development.

The authors thank Rocco Costantino and Giuseppe Vannelli for the support through their work.

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