Horizontal Air-Water Flow Analysis with Wire Mesh Sensor

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Abstract. A Wire Mesh Sensor, based on the measurement of the local instantaneous conductivity of the two-phase mixture, has been used to characterize the fluid dynamics of the gas–liquid interface in a horizontal pipe flow. Experiments with a pipe of a nominal diameter of 19.5 mm and total length of 6 m, have been performed with air/water mixtures, at ambient conditions. The flow quality ranges from 0.00016 to 0.22 and the superficial velocities range from 0.1 to 10.5 m/s for air and from 0.02 to 1.7 m/s for water; the flow pattern is stratified, slug/plug and annular. A sensor (WMS200) with an inner diameter of 19.5 mm and a measuring matrix of 16×16 points equally distributed over the cross-section has been chosen for the measurements. From the analysis of the Wire Mesh Sensor digital signals the average and the local void fraction are evaluated and the flow patterns are identified with reference to space, time and flow rate boundary conditions.

1. Introduction

The complexity of multiphase flows is due to the existence of multiple, deformable and moving interfaces, and to significant discontinuities of the fluid properties across the interface. As the interface distribution is the result of a mechanical and thermal dynamic equilibrium, several parameters affect the characteristics of a given flow pattern: the most important are the phases superficial velocity, the fluid properties (density, viscosity, surface tension, depending on the pressure and temperature), the channel geometry and the flow direction (upward, downward, co-current, counter-current). In horizontal and near-horizontal channels, that are used in the main cooling pipes of nuclear power plants, as well as in chemical plants and oil pipelines, stratified and slug flows are the most common flow patterns. Several experimental techniques have been proposed for the characterization of the flow patterns and for the measurement and modelling of the flow parameters [1-4]. One of the most important parameters that are used to characterize two-phase flows is the gas fraction, or void fraction, that is a dimensionless quantity indicating the volume (or cross section) fraction occupied by the gaseous phase. It determines many other important parameters such as the mixture density and viscosity, and the relative averaged velocities of the phases, and allows one to identify the flow pattern and to evaluate the heat transfer coefficient and pressure drops. The void fraction can be measured by means of a number of techniques, including radiation attenuation (X or γ-ray or neutron beams) for line or area averaged values, optical or electrical contact probes for local values, impedance techniques by using capacitance or conductance sensors and quick-closing valves based on the phases volume measurement. The use of the different techniques depends on the applications, and whether a volumetric average or a local void fraction measurement is desired. Wire Mesh Sensors (WMS), based

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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 [4–8]. One of the first studies of the void fraction measurement by means of the WMS has been proposed by Hardy et al. [4]: the string (wire) probe consisted of two parallel set of 12 electrodes, able to detect the impedance variation of the mixture between any two pairs of wires. The first tomography WMS, with approximately 100 frames per second, has been described by Reinecke et al. [5]: it is based on the measurement of the instantaneous conductivity of the two-phase mixture between all pairs of adjacent parallel wires of three electrode grids; the obtained three projections are subsequently used for a numerical reconstruction of the two-dimension gas fraction distribution. Prasser et al. [6] have developed a new WMS able to measure directly the conductivity between pairs of crossing wires to avoid tomography reconstruction algorithms and to increase the space and time resolution. The WMS has been used, in different geometry and for different configurations, to study mean cross-sectional void fraction and gas profile evolution [7]. Da Silva et al. [8] have developed a WMS system based on permittivity (capacitance) measurements, which has been applied to investigate multiphase flows involving non-conducting fluids. 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), for several flow patterns: local, chordal, cross-sectional void fraction values are derived from the sensor data and the flow pattern evolution in time and space is analyzed and discussed by means of a statistical analysis. The dependence of the signals from the measured fluid dynamic quantities is discussed too.

2. Wire Mesh Sensor geometry and electronic circuit
The present work is based on the WMS that has been developed by Prasser [6] and constructed by Teletronic Rossendorf GmbH [9]: the sensor working principle is the measurement of the conductivity of the fluid. Because air and water have different electrical properties (water is high conductive while air is practically an ideal insulator) the measurement of the conductance can be analyzed to detect the presence of each phase inside the pipe.

The WMS used in this work (figure 1) 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 have a diameter D_wire of 70 µm and a pitch equal to 1.3 mm, so that only the 5.4% of the pipe section is occupied by the sensor. The measuring grid allows one to obtain a spatial resolution larger than 1.3 mm and, due to the high time resolution (up to 10,000 frames/s), the evolution of the investigated flow pattern can be analyzed. In the present study the local conductivity in the gaps of all crossing points is measured at a frequency of 1250 frames/s (but the sampling frequency can be increased up to 10,000 frames/s [9]).

3. Experimental facility and test matrix
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 m³/h with a ±0.5% r.v. accuracy value. At lower flow rate the water enters inside the test section radially through a pipe of 10 mm that connects the mixer device with the feed water loop, and the flow rate is 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 consists of a 19.5 mm diameter and total length of about 6 m
horizontal pipe; two straight portion of pipe having lengths of 4000 m and 2000 m respectively are
connected by a 90° horizontal elbow. The WMS is installed in the second portion of the test section
between two Plexiglas pipes having a length of 600 mm. 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. The mixing zone is
connected with the test section by a pipe made up of an horizontal part and a short vertical part
connected by two 90° elbows. Experiments have been performed at water temperature of about 20 °C.
At the inlet of the test section the pressure is measured using an absolute pressure transducer
Rosemount 3051/1. In the presented tests the liquid flow rate ranges from 0.0083 kg/s to 0.512 kg/s
while the air flow rate ranges from 0.083 g/s to 3.9 g/s; the flow quality ranges from 0.00016 to 0.22
and the superficial velocity ranges from 0.1 to 10.5 m/s for air and from 0.02 to 1.7 m/s for water; the
pressure ranges from atmospheric pressure to 2.6 bar depending on the experimental conditions. The
tests have been performed by fixing the water flow rate and by increasing the air flow rate for each
run. The absolute pressure is measured at the inlet of the test section and the volumetric void fraction
is measured in the 1200 mm long first part of the test section. The typical observed flow patterns are
stratified flow, intermittent flow (slug and plug) and non symmetric annular flow.

4. Experimental methodology and signal processing
The WMS sensor are acquired by means of WMS200 electronics and processed in Matlab®
environment, at a frequency of 1250 frames/s for each run, for a total time of 20 s. The output is a 3-D
matrix $V(i,j,k)$, where the indexes $i$ and $j$ refer to 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 taken into account the wall influence, while the points, that are located outside the cross
section of the pipe are excluded from the analysis. There is not a wire crossing the center of the pipe,
and the wires closest to the pipe symmetry axis ($i$ and $j$ indexes equal to 8 and 9 in horizontal and
vertical direction respectively) are 0.65 mm (half of the grid pitch) far from the origin. 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:

$$V(i,j,k) = \frac{V(i,j,k) - V_\text{a}(i,j)}{V_e(i,j) - V_\text{a}(i,j)}$$

where $V_\text{a}$ and $V_e$ are the time average values of the signals with the pipe filled with water or air at the
beginning of the test.

5. Local void Fraction and cross-sectional void fraction
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 $p$ are assumed. The mesh points near the pipe wall refer to a fraction of the square
section area. A matrix of weight, $a(i,j)$, takes into account the reference area: associating at each
crossing point the square section equal to $p^2$ (where $p$ is the 1.3 mm pitch), the weight is evaluated as
one if the reference area of the point is inside the pipe cross section and as $s/p^2$ ($s$ is the fraction of the
area inside the pipe) if a portion, or the total of the reference area of the point is outside [6].
Then the local instantaneous void fraction is derived as:

$$\alpha(i,j,k) = \frac{V(i,j,k) - 1}{a(i,j)} + 1$$

From the time history of the local void fraction the time average values are derived. In order to
characterize the flow pattern, the time average value $a(i,j)$ and the variance $\sigma_a(i,j)$ are calculated as:
\[ \alpha(i, j) = \frac{1}{k_T} \sum_{k=1}^{k_T} \alpha(i, j, k) \]  

(3)

\[ \sigma_{\alpha}(i, j) = \left[ \frac{1}{k_T} \sum_{k=1}^{k_T} (\alpha(i, j, k) - \alpha(i, j))^2 \right]^{1/2} \]  

(4)

Where \( k_T \) is the number of measured frames (equal to \( fT \)), \( f \) is the acquisition frequency (1250 Hz) and \( T \) is the measuring time. The standard deviation distribution analysis is used to derive the amplitude of the interface oscillations in stratified flow. In slug flow the variance distribution allows to obtain information concerning the amplitude and the frequency of the pulsating flow. Finally the average cross-section value \( \alpha(k) \), is calculated as:

\[ \alpha(k) = \frac{1}{\sum_{i=1}^{16} \sum_{j=1}^{16} \alpha(i, j)} \cdot \sum_{i=1}^{16} \sum_{j=1}^{16} \alpha(i, j, k) \alpha(i, j) \]  

(5)

The time history of the average void fraction is characterized by the time standard deviation and by the probability density function PDF.

6. Void fraction chordal profiles and phase distribution

From the calculated local void fraction the time average chordal profiles are derived. The chordal profiles are used to analyze the symmetry of the flow and reconstruct the vertical mean void fraction profile. Figures 2 (a) and 2 (b) show the effect of the liquid superficial velocity at low and high values of gas superficial velocity on the time average vertical void fraction distribution for \( i=8 \). Figures 2 (c) and 2 (d) show the effect of gas superficial velocity for two different liquid superficial velocity values. The vertical direction is normalized by means of the pipe diameter: \( r/D = 0 \) at the bottom of the pipe, \( r/D = 1 \) at the top of it. The results show three typical regions: a bottom region with void fraction near zero (lower than 0.02); an intermediate region where the void fraction increases from 0.02 to high void fraction values (higher than 0.65-0.7) and a top region where the void fraction is higher than 0.07. At low air velocity the flow is characterized by a smooth stratification that becomes wavy by increasing the water flow rate. The increase of the air flow rate (figure 2 (b)) produces a thinner liquid film in the most cases and an intermittent flow that evolves in slug flow by increasing the water flow rate (figure 2 (d)), or in annular wavy flow at higher air flow rate and lower water flow rate (figures 2 (b) and 2 (c)).

Figure 3 shows typical time average void fraction profiles for different \( J_g-J_l \) values and the corresponding local standard deviations: the run (a), classified as stratified, is characterized by a sharp variation of the void fraction values between \( r/D=0.3 \) and \( r/D=0.4 \). The value of the void fraction is about zero below and one above it. The corresponding standard deviation value is equal to zero in the upper part and at the bottom of the pipe, always occupied by the gaseous phase and liquid phase respectively. The profile of the standard deviation reflects the stochastic behavior of the interface and the amplitude of the interface oscillations: only in the region between \( r/D=0.3 \) and \( r/D=0.4 \) it is small (lower than 0.05). The signals of figure 3 (c) show higher standard deviation values in the bottom of the pipe, due to oscillations of the interface, typical of annular-wavy flow. In the central region of the pipe (core region) the void fraction is always equal to one, as confirmed by the standard deviation profile, but near the upper wall a lower value of the measured \( \alpha \) value reveals the presence of the thin liquid film. The run (b) of figure 3, that is typical of low gas velocity, shows that the bottom part of the pipe is still covered by the liquid phase, as in a stratified flow, but in the upper part the presence of a peak and the standard deviation profile shows the presence of slugs precursor.

By increasing the air velocity the profile in the pipe core region tends to flat, as for runs (c) and (d) with a strong stratification and a higher standard deviation of local void fraction: these runs are characterized by void fraction values between 0.4 and 0.5 (run c) and between 0.4 and 0.8 (run d) The analysis of the standard deviation allows to highlight that the slugs cover the entire cross section of the pipe as it can be seen by the rather constant value of the standard deviation.
Figure 2. Void fraction vertical profile

Figure 3. Void fraction vertical profile and standard deviation for different runs. (a) $J_g = 0.23 \text{ m/s}$, $J_l = 0.05 \text{ m/s}$, (b) $J_g = 0.14 \text{ m/s}$, $J_l = 1.71 \text{ m/s}$, (c) $J_g = 0.71 \text{ m/s}$, $J_l = 1.42 \text{ m/s}$ (d) $J_g = 1.33 \text{ m/s}$, $J_l = 1.42 \text{ m/s}$ (e) $J_g = 10.5 \text{ m/s}$, $J_l = 0.05 \text{ m/s}$

7. Interface time evolution and liquid level

From the analysis of the time chordal profile, the air-water interface evolution is derived. A threshold value, $\alpha(i,j,k)=0.1$, is chosen to define the interface, and by a simple algorithm the liquid level $h(t)$ in the pipe is reconstructed as reported in figures 4, 5 and 6. For a given gas velocity and very small liquid velocity slugs are observed with a relative high frequency ($1/T$ higher than 8 s). As shown in figures 4 and 5, following a passage of the slug the liquid level drops to the lowest values, as the liquid
in the stratified flow is swept up by the slug, enabling the cycle to repeat. As the superficial liquid velocity increases the number of roll waves and the slug frequency increase as shown in figures 4 and 5.

The $h/D$ values obtained from the sensor signal do not always reach a value of unity when a slug passes because of the presence of gas bubbles. At higher superficial gas velocities, when the observed flow pattern is annular-wavy, many waves on the gas-liquid interface occur as shown in figure 6. The presence of the liquid film in the upper part of the tube is not clearly detected by the sensor because the film is very thin due to gravity effect. The analysis of the interface evolution allows to identify the minimum of the reference liquid level $h_{min}$. Figure 7 shows $h_{min}$ as a function of the phases superficial velocity: in the tested range $h_{min}$ significantly decreases with increasing superficial gas velocity and slightly increases with increasing superficial liquid velocity. At lower superficial gas velocities, the $h_{min}$ significantly depends on the liquid velocity, while such dependence is poor when $J_g$ is higher than 2 m/s.

8. Average void fraction analysis

In figure 8 the average cross-section void fraction time evolution is presented for four different two-phase flow conditions. From the comparison of the flow evolution at different superficial velocity different regimes can be identified. In figure 8 (a) the average cross section void fraction for stratified flow is shown: a constant value of the void fraction is not reached due to interface wave oscillations. By increasing the phases mass flow rate the flow becomes intermittent. As shown in figures 8 (b), (c) and (d) several sub-regimes can be distinguished depending on the superficial velocity of the liquid and gas phase. A typical slug unit, according to [2], consists of a liquid slug zone of length $L_s$ and an elongated bubble zone of length $L_b$ with a liquid film under the long gas bubbles (stratified zone): because of the velocity of slugs two transit times $\tau_s=L_s/v_s$ and $\tau_f=L_f/v_f$ are defined. In figure 8 (b) many features of other flow regimes are shown: aerated slugs can be observed, small bubbles in the wavy liquid layer at the bottom of the tube and dispersed water droplets in the gas phase appear. At higher superficial gas velocities, figure 8 (c), the flow pattern is identifiable as slug flow: the time
evolution is characterized by elongated liquid slugs and stratified flow zones with low interface oscillations. By increasing the gas flow rate, the frequency of the slugs strongly increases, as shown in figure 8 (d). This flow regime is more turbulent than the elongated bubble flow regime: the slugs increase in velocity and become shorter. At air superficial velocities higher than 3 m/s the liquid flow tends to produce a very thin film also in the upper wall, while the interface in the lower part of the cross-section becomes strongly wavy and the flow having these characteristic is classified as annular-wavy.

The PDF is evaluated for 100 equally spaced points that cover the range of the data: for lower air and water velocities (a) the PDF is a distorted unimodal function centered in the mean void fraction value; for intermittent flow (c) the PDF is clearly a bimodal function with the two maximum at very low (0.1) and high (0.7) void fraction; the lower void fraction values are still the most expected value. For the flow conditions (d) the PDF is still a bimodal function, but in this case the expected value is represented by 0.8. value of void fraction: the annular-wavy flow, is determined by a function shaped as unimodal with the maximum probability at very high void fraction ($\alpha$ higher than 0.9).

9. Comparison with quick closing valves method
The average void fraction for each run is evaluated by using the equation (5) and is compared with the volumetric void fraction that is measured by the quick closing valves (QCV) method; because of the intermittence of the flow the void fraction measurement by QCV method is repeated several times for
each flow rates combination in order to get a representative mean value. Figure 10 presents the comparison of the measured void fraction as a function of the experimental flow quality between the QCV and WMS methods. Compared to the QCV void fraction, the WMS void fraction shows a higher dispersion in the range of intermittent flow and it is in good agreement at very high void fraction when the flow becomes annular. Moreover the WMS gives lower values of void fraction at flow quality higher than 0.01 and higher values at flow quality lower than 0.001. It must be observed also that the volumetric void fraction is an average value along the test section; it is measured at the entrance of the test section, where the flow is not completely developed and the effect of L/D is fundamental to characterize the flow [2-3].

10. Conclusions
In the present study the phases distribution of air-water horizontal two phase flows has been measured by WMS at different superficial flow velocity. The signals of the sensor, that are proportional to the liquid conductivity, are processed to get the time-dependent and average chordal profiles and the cross-section void fraction. The effects of the superficial liquid and gas velocity on the void fraction profiles evolution have been experimentally investigated. The experimental results give important informations about the phase distribution inside the pipe, as the local and time average void fraction, the interface evolution, and the transit time of slugs or plugs. The large amount of data produced by the WMS requires to develop a methodology for on line analyses with reference to the run conditions: pressure, superficial velocity, temperature, phase conductivity. The future work will be addressed to develop a methodology for the on line characterization of the flow (flow pattern, local time average void fraction, interface profile, characteristic times and frequency of slugs) and to extend the analysis to a couple of sensors for cross-correlation analyses and to measure the velocity profiles for the complete characterization of the flow.

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