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A Multi-Tip Probe for the Measurement of the Phase Velocities in Gas-Liquid Flows

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The characterization of gas-liquid flows involves the measurement or prediction of temperature, pressure and velocities, plus some quantities which describe the flow structure. Concerning the latter, the most used is the local void fraction, which in this work is accompanied by the flow complexity, another quantity which evaluates the number of interfaces passing through a point during the sampling interval. The cross-section averaged value of the flow complexity may be put into relation with the liquid velocity. In horizontal ducts, such correlation may assume a very simple potential form or a slightly more complex aspect if the effect of flow development along the duct is included. It can be also determined by detection of the phase density function at different heights on the vertical diameter of the duct cross-section alone. Therefore the liquid velocity and consequently gas velocity (via slip correlations) can be estimated by inline phase density measurements using local impedance probes. The paper presents the preliminary analyses to develop the correlation and the design of a multi-probe sensor to perform the measurements.

1. Introduction

Two-phase flows, and particularly fluid-fluid flows, have a widespread application, which spans from oil extraction and transport to power generation, chemical plants and many other industrial processes. This assigns a great importance to a deep understanding of their behaviour, as it may have a deep influence (up to critical effects, e.g., burnout or pipe choking) on the involving systems and their performance. In addition to the section-averaged, one-dimensional models, local investigation may provide both a basic knowledge about the flow structure, the distributions of the phase velocities and of the interface between the same. It is a support in the management of mass, momentum and energy balances for more complex and detailed models, such as the two-fluid model (Ishii and Hibiki, 2006); moreover, local investigation is the only way to calculate averaged values of the quantities for which no area-averaged or volume-averaged measurement techniques exist. In addition to the well-known local void fraction, another quantity able to describe the interfacial structure of the flow is needed: at fixed void fraction the flow structure changes according to the superficial velocities when different flow patterns come out. A natural choice would be the interfacial area concentration, which appears from the equations modelling the jump conditions at the interface and which can be defined both in local and averaged terms (Ishii and Hibiki, 2006). Regrettably, its measurement is far from being an easy task and requires very sophisticated, complex and expensive instrumentation, e.g, γ-ray, X-ray, or ultrasound tomography, magnetic resonance imaging, wire-mesh sensors. Other quantities may be therefore more suitable when the aim is only to characterise the flow structure. The flow complexity, which evaluates the number of flow structures, will be used in this work. It may be used in synergy with the void fraction both in local terms (Arosio and Guilizzoni, 2006) and after cross-section averaging. In this second use, a promising correlation appears between the void fraction, the flow complexity and the fluid velocities (Arosio and Guilizzoni, 2011), which may be used to design a new device for the inline measurement of the mass flow rates of the phases. This paper summarizes some forms of such correlations and shows the preliminary design of the sensor, from both the mechanical and electronic points of view.

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2. Definition of the quantities

The local void fraction α_P is a dimensionless, time-averaged quantity that can be defined as the probability for a point inside the flow to be immersed in the gaseous phase (Delhaye, 1968). It can be calculated as the average of the phase density function $\delta(\boldsymbol{p},\tau)$, which is a local instantaneous quantity defined as 1 if at instant τ point $\boldsymbol{p}$ is immersed in the gaseous phase and 0 if at instant τ point $\boldsymbol{p}$ is immersed in the liquid phase. As the detection of the phase density function is performed by means of discrete sampling, the time averaged local void fraction is calculated as the arithmetic mean of the acquired signal. The local flow complexity $\xi_P(\boldsymbol{p},\tau,\Delta\tau)$ is dimensionless and intrinsically time-averaged too. It measures how much "complex" the flow structure is by calculating the ratio between the number of 0-1 and 1-0 transitions in the $\delta(\boldsymbol{p},\tau)$ signal during the sampling interval $[\tau,\ \tau+\Delta\tau]$ (i.e. of interfaces through point $\boldsymbol{p}$) and the maximum number of potential transitions in the same (which is equal to the number of samples minus one). Single phase flow through point $\boldsymbol{p}$ would give $\xi_P = 0$. The theoretical upper limit would be 1, but measured complexities seldom exceed 0.4. A weakness of ξ_P is that its values depend on the sampling frequency, which changes the total number of samples and the number of detected interfaces in a non-proportional manner. A modified version (also called interference frequency) evaluates the number of detected interfaces per second, removing the frequency dependence at the price of being no longer dimensionless. In this work the first definition will be used, but all the results apply identically to the second too. While the cross-section averaged void fraction α can be directly determined through 2D- or 3D- averaged detection, e.g. by means of the already cited techniques or by impedance measurements (Reinecke and Mewes, 1996), the averaged flow complexity ξ can only be calculated from a grid of local measurements. They are then weighted to calculate a cross-section averaged value, where the weights are given by the ratio between the area of each cell centered in the experimental point and the duct cross-area. The same procedure was followed in this work to calculate the cross-section averaged void fraction too.

3. Experimental setup and procedures

Data processed in the present work were acquired during different trials carried out at the Multiphase Thermo-Fluid Dynamics Laboratory of the Department of Energy, Politecnico di Milano. The experimental rig consists of a closed loop for the liquid phase (water) and an open loop for the gaseous phase (air), sharing a 12m-long, transparent Plexiglas® stretch where the two-phase flow sets up. Such test section can be equipped with different ducts. The analysis presented hereinafter included measurements on circular pipes, both on constant diameter ducts (60 mm i.d., referred to as CD60 in the following) and on the upstream sections of two ducts with sudden section changes: an expansion from 60 mm i.d. to 80 mm i.d. (SE6080 in the following) and a contraction from 80 mm i.d. to 60 mm i.d. (SC8060 in the following). Along the test section, local probes are placed to sample the phase density function in each point of interest. Both optical and impedance probes having a different tip size were used and no significant disagreement between the two types was found. The raw phase density signals were fairly well defined for all the investigated regimes, and they were sampled at 10 kHz for at least 180 s in order to reduce the progressive average within ±0.5 %. The use of local probes to sample the phase density function is affected by known limitation and errors (Cartellier, 2001), with different effects on α and on ξ, which at present appear very difficult, if not impossible, to evaluate. Yet, for the scopes of the present work such issues are of minor importance because the correlations described in the following subsist in any case (Arosio and Guilizzoni, 2011). Further details on the experimental setup and procedures, including sketches of the setup and of the grid of experimental points used to calculate the cross-section averaged values, can be found in Guilizzoni (2013). The experiments were performed on air-water flows at room temperature with liquid mass flow rates from 2 to 7 kg/s and volume gas fractions from 0.25 to 0.85, i.e. liquid superficial velocity j_L ranging from 0.6 m/s to 2.5 m/s and gas superficial velocity j_G from 0.26 to 7.2 m/s. In all cases intermittent flow patterns, in the plug and slug regions, were observed.

4. Correlation between the flow complexity and the liquid velocity

The total interface area in a heterogeneous medium can in general be linked to some energy content of the medium itself, as the interfaces are regions with a higher energy density with respect to the bulk phases. For a two-phase flow, the interface area concentration can be related to the energy of the flowing mixture. This was proven for bubbly flows by the pioneering analyses and experiments by Kolmogorov, Hinze, Sleicher and other authors, which studied the break-up and coalescence phenomena in a two-phase flow to predict the stable dimensions of bubbles or drops in a turbulent flow. A review of such investigations can be found in (Angeli and Hewitt, 2000). A common finding of those studies is that the maximum bubble diameter is related to the velocity of the carrier fluid. For horizontal, adiabatic gas-liquid flows this is not surprising because, once fixed the internal and potential energies, the energy content is mainly characterized by the kinetic term of the liquid phase, while the kinetic energy of the gaseous phase appears to be largely negligible with respect to the first. For intermittent flows the size distribution of the dispersed phase is obviously different from the case of bubbly flow, because large structures (plugs or slugs) are present in addition to the bubble population. Nevertheless, the total number of interfaces in the flow is still affected for the vast majority by the number of the small bubbles. Thus, a correlation can be expected between the flow complexity and the liquid velocity. Experiments confirmed this: Figure 1 shows the $\xi = f(w_L)$ diagram for all the acquired points. Markers shape is drawn to show the independence of the correlation from the duct diameter. For CD60 data, marker gray tones are also proportional to the gas superficial velocity j_G, to evidence a slight dependence of the correlation on the latter quantity too (which will be neglected in the following).

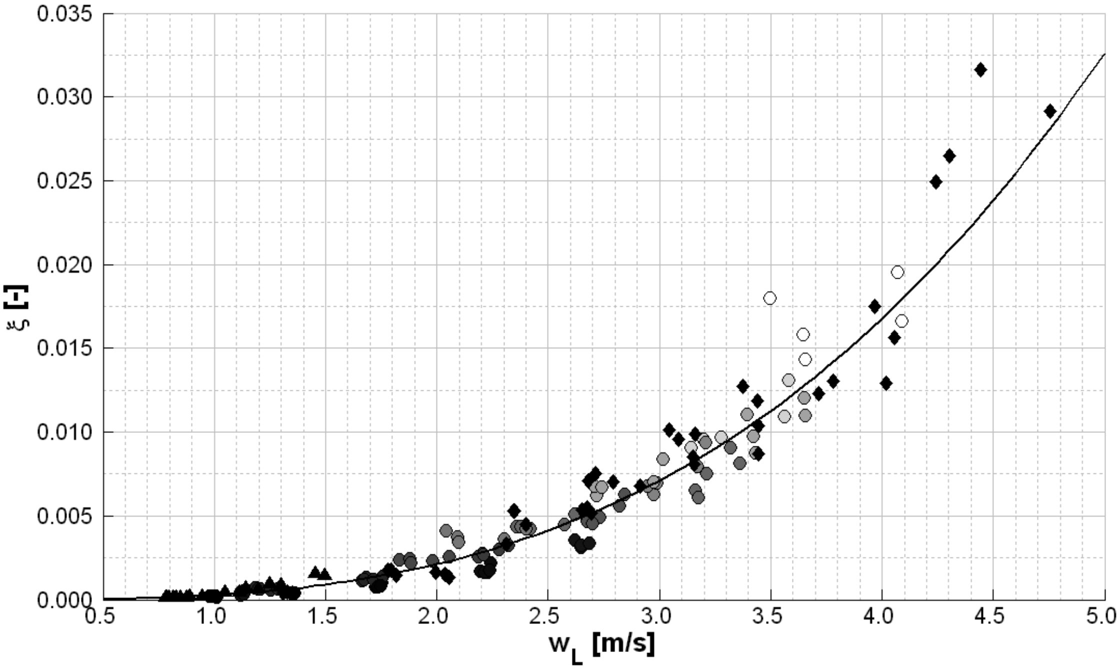

Figure 1: $\xi = f(w_L)$. Circles CD60, triangles SE6080, diamonds SC8060. For CD60, marker gray tones are proportional to j_G (lighter means higher j_G). The continuous line represents Equation 1.

A correlation having a simple potential form can be therefore obtained by regression on all the available experimental data:

$$\xi = C_1 w_L^{C_2} \tag{1}$$

where C_1 = 0.000269 [$(s/m)^{C2}$], C_2 = 2.98 [-]. The resulting trend is shown in Figure 1 too. It is worth noting the value of C_2: it is very close to 3, which may indicate that, apart from experimental "noise" in the fitting, the flow complexity depends on the kinetic power of the liquid stream (which may be expressed as the product between the mass flow rate and the kinetic energy per unit mass, i.e., as $\rho_L w_L A_L \cdot w_L^2 / 2 = 1/2 \rho_L A_L w_L^3$). Such exponent is also in good agreement with the value of 2.5 found by Sleicher (Angeli and Hewitt, 2000), particularly if considering that the latter evaluated the bubble maximum diameter and consequently minimum bubble number. The mean absolute error (MAE) of such correlation in the prediction of ξ is 23.5 %, with a standard deviation of the error of 20.9 %. As cross-section averaged void fraction can be measured using area- or volume-averaging techniques, a first use of such correlation may be to directly estimate the flow complexity without the need to perform time-consuming local measurements. A second, "inverse", use of the correlation is even more promising: given the values of both the cross-section averaged void fraction and flow complexity, estimation of the liquid velocity (and consequently mass flow rate) is possible. From the latter, w_L can be then directly calculated. In this case, the MAE is 7.5 %, with a standard deviation of the error of 5.9 %. The conversion of the correlation into a dimensionless form, e.g. using the liquid Reynolds number or another appropriate Reynolds number, adds no real information (as all the other quantities do not vary apart from the duct diameter), while it seems to slightly worsen the fitting (around 2 % in the MAE, which is in any case lower than the experimental uncertainty). Further improvements in the accuracy can be obtained if the correlation coefficients are fitted on reduced data sets, e.g. if only the D60 data are used the coefficients in the correlation become C_1 = 0.000244 [(s/m)^{C2}], C_2 = 3.06 [-].and the MAE is reduced to 18.2 % (standard deviation of the error 17.7 %). A more complex form of the correlation could be then obtained expressing C_1 and C_2 as functions of the gas superficial velocity: this improves the accuracy in ξ prediction, but it also forces to use an iterative procedure in the inverse use, so it will not be discussed here. Following further the same approach of "tailoring" the correlation to the specific flow conditions which are present in the duct section of interest, a slightly more complex form of the correlation can be proposed. It takes into account the flow development after the mixing section and the density variations of the gaseous phase due to the pressure drop along the duct:

$$\xi = \left[C_3 + C_4 \ln\left(\frac{\alpha^2}{z/D} \right) \right] w_L^{C_5} \qquad (2)$$

where C_3 = 0.000629, C_4 = 0.0000570, C5 = 3.047, with dimensions as they result from the equation. The MAE in this case is 8.7 % (standard deviation of the error 6.7 %) in the prediction of ξ, while it is 3.0 % (standard deviation of the error 2.5 %) in w_L estimation. Once the liquid velocity is known, the gas velocity w_G can be estimated using correlations for the slip between the phases. The resulting accuracy in the evaluation of w_G obviously depends also on the accuracy of such correlations. Regrettably, the uncertainty in such correlations is very high (at least 15-20 %), despite the large number of them which is available in literature (Woldesemayat, 2007). Therefore, the development of a slip or void fraction-volume fraction correlation for each investigated duct configuration seems at present to be unavoidable to grant good accuracy to the prediction of w_G too. The hereinabove described method suffers from the binding experimental detection of the cross-section averaged values by means of multiple local test, which is extremely time-consuming and would prevent a practical inline use in industrial applications. Such issue can be overcome if the local values are only acquired along the vertical diameter of the section of interest and the area-averaging is performed using horizontal slices of the duct cross-section as cells, vertically centered in each measurement point. The difference between the actual cross-section values of the quantities and their estimates α_S and ξ_S from such a reduced set of points obviously depend on the flow pattern and on the distribution of the phase on the section of interest. An analysis of the characteristics of such distributions can be found in Arosio and Guilizzoni (2008). Nonetheless, the correlation between the flow complexity and the void fraction is still very good when using ξ_S and α_S to estimate the liquid velocity. The MAE in the prediction of w_L becomes 8.8 % (standard deviation of the error 6 %) when using Equation 1 with coefficients C_{1F} = 0.000198, C_{2F} = 3.37 and 5.7 % (standard deviation of the error 4.9 %) when using Equation 2 with coefficients C_3 = 0.000492, C_4 = 0.0000477, C5 = 3.473.

5. The multi-tip probe

The possibility to estimate the cross-section averaged void fraction and flow complexity by means of the measurement along the vertical diameter alone led to the development of a device able to perform such acquisitions inline. The proposed device is pretty much a simplified version of the linear array of probes already proposed in literature (Sekoguchi and Mori, 1997). The aim is to create a simple and robust tool which may be suitable for field use. It consists of a supporting plate to which a series of sensing tips are fixed. The number of tips and their positions along the vertical diameter have to be chosen as a compromise between theoretical accuracy (which would require an high number of sensing elements), mutual interference between the tips (both fluid dynamic and electric) and between the tip set and the flow itself (fluid dynamic distortions which may affect the measurement). They may be optimized depending on the flow pattern. Using at least ten tips, which is one half of the number of points used to develop the correlations, still gives a good reconstruction of the complete α_S and ξ_S profile along the vertical diameter if spline interpolation is implemented to reconstruct the points which are not directly measured. Each tip is a local impedance probe (Teyssedou et al., 1988), as they are more suitable than optical probes both due to their extremely lower cost and to their much higher mechanical resistance. The working principle of a single impedance probe exploits the low electrical resistance of water with respect to the high resistance of air. A thin conductive stem, completely insulated except for the tip, is immersed in the flow with the latter positioned in the point of interest. A second conductor is placed on the bottom of the duct, long enough to assure that at least a part of it is always covered by water, so that it can be used as the ground reference. When the measuring tip is immersed in water too, a low-resistance path closes between the tip and the ground reference, otherwise only a high (ideally infinite) resistance path is present. Corresponding difference of potential is therefore present between the two electrodes and sampling it gives a signal which is related to the ‘‘instantaneous’’ air and water presence in the point of interest. Proper filtering (using one or two thresholds) is then used to convert such analog signal into a digital Boolean signal. More details will be given in the following.

5.1 Mechanical design of the sensor

Figure 2a shows a sketch of the proposed device (with 19 equally spaced tips). A printed circuit board is used as supporting plate, on which conductive pathways carry the acquired signals from the sensing tips to an output port. Stainless steel needles were chosen as sensing tips, as they offer the best compromise between electric conductivity and mechanical and chemical resistance. In addition to not breaking, the tips must not bend when they are invested by the intermittent flow. Moreover they should show minimal oxidation, as even a very thin oxide layer worsens the sensitivity of the device. The needles protrude by 15 mm from the PCB and they are completely painted with an insulating glaze coating (e.g. enamel, as for transformers), apart from the tip which constitutes the sensing element. From the output port the signals are then carried to the acquisition system by means of insulated and shielded cables, to reduce mutual interference. To complete the electric insulation and to shield the device from the flow, the whole sensor body is enameled too. A less wearable choice, which may be better for industrial use, would be the insertion of the device into a polymeric or glass shell, whose shape could also be optimized from the fluid dynamics point of view to reduce the disturbances exerted on the flow. In any case, similarly to other intrusive sensors – e.g. linear array of probes (Sekoguchi and Mori, 1997) or wire mesh sensors (Pereza et al., 2010) – the proposed one should affect the flow mostly after the measurement itself, as the sensing tip protrudes towards the incoming flow, which encounters them before reaching the sensor body.

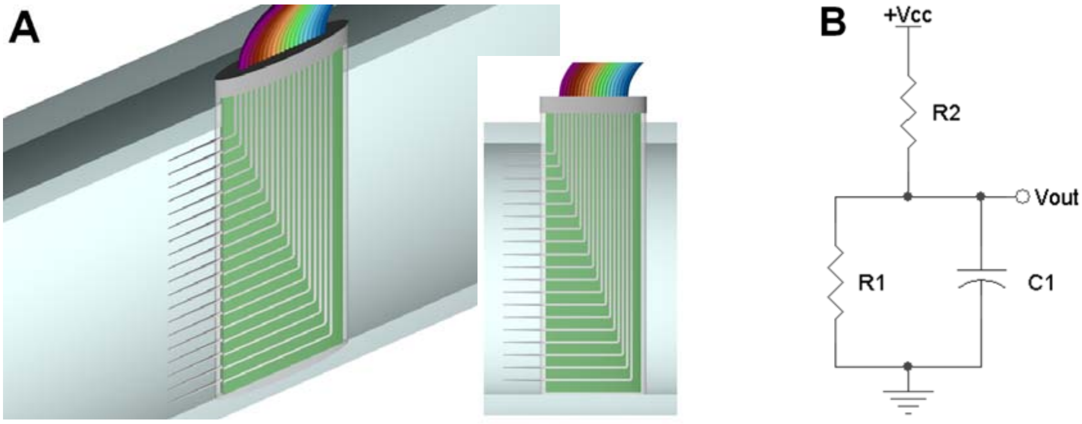

Figure 2: a) Sketch of a multi-tip probe with 19 equally spaced tips, b) Electrical model of one needle of the probe as an electrical parallel resistor capacitor network.

5.2 Electronic design of the sensor

The electronic controller of the sensor works as follows. To avoid the interferences due to resistive closed paths between the sensor needles it is necessary to activate one needle at a time and to isolate the others. The electrical model of each needle (Figure 2b) is as electrical parallel resistor capacitor network (R_1 and C_1 in the figure). The R_2 resistor is used to polarize the needle and to create a voltage divider so that the two case of low and high resistance can be recognized. The control electronic is composed by a micro controller unit with a dedicated firmware which has the following functions: polarize one needle at a time, acquire the output voltage from the voltage divider (R_1 and R_2 in Figure 2b), detect the phase by comparing the acquired voltage with the thresholds which are internally calculated on the basis of the measure in the two cases of low and high resistance, send the results to a personal computer for storage and post-processing. More in detail, the firmware is based on a finite state machine that schedules all the functional steps. The sequence of the operations is (N is the current needle polarized, N goes from 1 to the total number of needles of the probe):

1. Polarize needle N, isolate the other needles and acquire the output voltage using the internal analog to digital converter;
2. Store the acquired values for the threshold calculations relevant to needle N;
3. Compare the acquired values with the actual threshold of needle N and decide if water or air were detected;
4. After 10 measures recalculate the threshold relevant to needle N, using the median value of the acquired values. This step is necessary to compensate for the oxidation of the needle tip and eventual other effects;
5. If all the needles have been processed then send the results to the computer and restart the algorithm from the first needle, else restart the algorithm for the next needle N+1.

6. Conclusions

A correlation between the flow complexity and the liquid velocity has been proposed for intermittent air-water flows in circular horizontal duct. It has been developed in a few different forms. In addition to the possibility to predict the flow complexity from known liquid velocity and void fraction, such correlation allows to estimate the liquid velocity from the void fraction and flow complexity. As the latter can be obtained by means of phase density acquisitions, a sensor was designed that is able to perform inline measurement of the liquid velocity. It is based on multiple local impedance probes and a micro controller to operate and monitor them. The preliminary studies are promising, actual development and testing of the sensor is at present in progress.

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