NONLINEAR DYNAMICS OF AIR-WATER MIXTURES IN VERTICAL PIPES: EXPERIMENTAL TRENDS

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This study reports the results of the characterization of an air-water two-phase experimental apparatus and the preliminary analyses of the experimental time series. The test section of the apparatus consists of a vertical pipe equipped with an impedance void fraction sensor. The carrying frequency of the impedance sensor has been chosen in order to operate it as a resistive sensor. The calibration of the sensor has been performed through comparison of the instantaneous two-phase mixture conductivity signal and the local actual dimension of the bubble as estimated from high resolution photograph. The calibration curve allows, therefore, reliable estimation of the void fraction time series.

A preliminary analysis of the time series has been performed both in time and frequency domains, evaluating also the time series autocorrelation. These analyses have pointed out the inadequacy of linear tools for the characterization of two-phase flow dynamics, which are nonetheless characterized by strong recurrence and autocorrelation, which need to be further exploited by mean of nonlinear analysis in phase space. Phase space representation of different typical flow patterns, corresponding to a succession of bifurcation, shows the high potential of nonlinear analytical tools, to be adopted in order to exploit the system dynamics.

Keywords: Two-phase flows; experimental nonlinear dynamics; void fraction; attractor morphology.

1. Introduction

Two-phase flows are at the basis of many relevant industrial applications, ranging from chemical and processing plants to power generation and oil pipelines. One of the discriminating factors governing the performance of most of the systems based on this kind of flows is indeed represented by the flow patterns established in the system. Flow patterns identification is therefore fundamental for appropriate performance evaluation in the presence of two-phase flows.

Bubbly, slug, churn and annular flows, obtained by varying the mass flow rates of the two phases, can be recognized as the main typical flow patterns reported in several classifications [Costigan & Whalley, 1997; Mi et al., 1998].

In the bubbly flow small diameter bubbles are dispersed in the liquid phase. The main characteristic is that coalescence phenomena, though present, are unable to produce air bubbles occupying the tube section, as it happens in the slug flow.

The slug flow consists in an intermittent flow of gas bubbles alternated to liquid slugs [Issa & Kempf, 2003], where the latter can be aerated or not, as a consequence of the entrainment of small gas bubbles. The flow rates of the two phases is determinant for the development of the bubble, which may range from short to elongated, depending on
the relative importance of the three main parts in which the bubble can be subdivided. These are:

— the head region, where the fraction of the tube section occupied by gas rapidly grows from zero to approximately the whole section (i.e. except for the thin liquid film separating the gas from the tube wall);

— the central region, where the tube section is occupied by the gas phase, again except for the liquid film at the tube wall; it is worth mentioning that the thickness of the liquid film may present relevant oscillations, especially if the central region is sufficiently developed;

— the tail region, where the gas occupying the tube section abruptly decreases to approximately zero (except for the presence of small dispersed bubbles entrained in the liquid slug that follows the bubble).

A main distinction can be drawn in the class of slug flow on this basis. In particular, the cap flow occurs when the bubble develops from the head directly to the tail and no central region can be observed. The proper slug flow can be considered that for which the relative importance of the three regions is comparable. Finally, the plug flow can be considered as a slug flow characterized by elongated Taylor bubbles, where the extension of the central region is markedly predominant with respect to head and tail regions.

In the churn flow the liquid film may continue to drain down the wall as in elongated Taylor bubbles and occasionally the waves may bridge the tube or fall within it. The annular flow consists of a thin annular film of liquid on the tube wall on which small ripples, interspersed occasionally with large disturbance waves, flow in a regular manner up the tube.

The possibility to efficiently characterize the various flow patterns strongly depends on the technique adopted to measure the void fraction. Several techniques have been proposed for the measure of the void fraction of two-phase flows, ranging from the measurement of the electrical impedance of two-phase mixtures [Devia & Fossa, 2003; Lowe & Rezkallah, 1999], to optical techniques based on the measure of the scattering of the interface between the two phases [Keska & Williams, 1999], to the measure of pressure drops in a specified piece of the pipe [Vial et al., 2000]. Among these techniques, impedance measurements seem to be recognized as the most reliable [Keska & Williams, 1999]; in fact, it is nonintrusive and, most important, less dependent both on internal disturbances and external factors. Two main classes of impedance sensors have been proposed in literature: resistive sensors [Devia & Fossa, 2003; Lucas & Walton, 1997] and capacitance sensors [Vial et al., 2000].

The various flow patterns seem to develop as a result of the interaction of several transport phenomena, ranging from the mentioned entrainment to coalescence of gas bubbles. As a consequence, the characterization of flow patterns is still confused and controversial; in fact it is somewhat dependent on the approach to analysis of the experimental void fraction time series.

Several studies have been devoted to analyze the dynamical behaviors that characterize two-phase flows in pipes, often on the basis of statistical [Mi et al., 1998; Watson & Hewitt, 1999; Keska & Williams, 1999] or spectral [Song et al., 1998; Hetsroni & Rozenblit, 2000; Sun et al., 2002] analyses of void fraction-related experimental time series, such as impedance or pressure fluctuations. Nonlinear techniques have been also adopted for the analysis of pressure fluctuations in horizontal pipes [Drahos et al., 1996] and in vertical bubble columns [Letzel et al., 1997] or of impedance fluctuations in vertical pipes [Jin et al., 2003].

The aim of the present study is to report the preliminary results of the analysis of two-phase flows detected in a vertical experimental test section. The following sections are devoted to the description of the experimental setup and to the description of the calibration procedure for an impedance sensor of the resistive type, which has been designed and realized in order to have sufficiently high spatial and temporal resolution. Such resolution has been considered fundamental in view of the application of nonlinear techniques for time series analysis.

The last section is devoted to presenting the results of some basic analyses of the experimental time series.

2. Experimental Apparatus

Figure 1 represents a scheme of the experimental apparatus set up for the present study.

The liquid is supplied by a reservoir by means of a pump. The liquid flow rate can be varied up to 150 l/min by means of a series of valves and bypasses placed at the outlet of the pump. An electromagnetic flow meter is used in order to measure the velocity and the mass flow rate of the water.
The air line is constituted from a pressure regulator (0–8 bar) and three air flow meters that can regulate the air flow rate in the range 0–200 l/min. The air is supplied to the mixing chamber by a pressurised tank fed by a compressor.

The test section is mainly constituted by a 3 m long vertical pipe of 0.24 m diameter. At the basis of this, there is a mixing chamber which connects the liquid line and the air line. In order to allow the degassing of the working fluid an open tank is placed on top of the vertical pipe.

The probe for the void measurement is placed in the test section at a distance greater than the entrance region (i.e. over 100 times the pipe diameter) from the mixing chamber, in order to assure a well established flow regime for the two-phase flow. A reference probe is placed uphill the mixing chamber on the liquid line. Both the probes are connected to an electronic circuit and an appropriate acquisition system.

2.1. Void fraction measurement

The volume fraction of a phase in a two-phase mixture can be determined by measuring the impedance of a mixture if a significant difference in the electrical properties exists between the two phases. As well known, the impedance is made up of both resistance and capacitance and a main choice in the design of the void fraction sensor is related to the excitation frequency, which determines the dominance of the resistive or capacitive behavior.

A mathematical model of an impedance probe can be briefly described as follows [Song et al., 1998]. The impedance ($Z$) of a flow medium can be measured by two electrodes and can be mathematically expressed by:

$$Z(f) = \left[ \frac{1}{R} + \frac{1}{i2\pi f C_d} \right]^{-1}$$

(1)

where $R$ is the fluid resistance, $C_p$ is the capacitance due to the polarization of fluid molecules at the electrodes, $C_d$ is the dielectric capacitance of the fluid and $f$ is the excitation frequency at the electrodes. In the case of a two-phase mixture, $R$ is a variable that depends on the difference of conductivity of the two-phase (e.g. water and air), $C_p$ is affected by the different dielectric constants of the two phases and $C_d$ is a function of the dielectric constant, excitation frequency and void fraction, if the conductivity and the dielectric constant of a nonconductive phase (e.g. air) can be assumed negligible with respect to those of the conductive phase. Using these electrical characteristics of a two-phase mixture, a void fraction can be determined by measuring either the resistance $R$ or capacitance $C_d$.

When the fluid conductivity is large, the measurement of capacitance $C_d$ requires a high frequency excitation in order to minimize the role of a resistance and eliminate the parasitic capacitance caused by polarization at the electrodes, as well as to avoid a significant effect of external disturbances on the measurement system. Thus, in order to overcome these problems, the measure of the resistance is usually preferred, whereas the influence of $C_d$ and $C_p$ on measured impedance should be minimized by keeping the excitation frequency in a range depending on the electrical properties of the liquid. When water is considered as liquid phase such range is 10–100 kHz, but the choice of a low value is preferred in order to eliminate the role of parasitic capacitance. For higher frequencies (above the megahertz) the behavior of the electrolyte becomes essentially capacitive: for this reason, impedance methods are usually classified as either conductance methods or capacitive methods.
The sensor that has been designed and realized for the present study operates in the resistive range; in fact, a carrier frequency of 20 kHz has been supplied by an external sine wave oscillator to both measurement and reference probe, by means of an operational amplifier to decouple the input impedance from the load impedance. A reference sensor was installed in the liquid line, as shown in Fig. 1, in order to eliminate the drift in void signals caused by the changes in electrical properties of the flow medium. Figure 2 shows the signal processing circuit. The instrumentation amplifier assures a high dynamic response and a perfect decoupling of the electronic circuit from the measuring section. The variable gain can be regulated by $R_G$ value. The amplified output is applied to the electronic rectifier. A cut-off frequency of 200 Hz was adopted in order to allow adequate removal of the carrier frequency and to avoid aliasing with the sampling frequency. The final output is sent to a PC-based data acquisition system at the sampling rate of 1000 Hz, to allow the recording of the main void fluctuations expected in the experiments.

The probe configurations considered in this study is sketched in Fig. 3.
Table 1. Operating conditions of experimental tests.

<table>
<thead>
<tr>
<th>Water [l/min]</th>
<th>0.8</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>1.2</td>
<td>3</td>
<td>7.2</td>
<td>29.4</td>
<td>5.4</td>
</tr>
<tr>
<td>1</td>
<td>1.32</td>
<td>2.4</td>
<td>8.4</td>
<td>30.6</td>
<td>5.34</td>
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<tr>
<td>5</td>
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<td>2.88</td>
<td>7.8</td>
<td>30</td>
<td>5.52</td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
<td>2.4</td>
<td>7.8</td>
<td>30</td>
<td>5.52</td>
</tr>
<tr>
<td>Air [l/min]</td>
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<td>1.2</td>
<td>3</td>
<td>7.8</td>
<td>30.6</td>
</tr>
<tr>
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<td>3.06</td>
<td>8.4</td>
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<td>5.46</td>
</tr>
<tr>
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</tr>
<tr>
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<td>2.82</td>
<td>7.5</td>
<td>29.4</td>
<td>5.46</td>
</tr>
<tr>
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<td>1.2</td>
<td>2.4</td>
<td>7.92</td>
<td>27.6</td>
<td>5.46</td>
</tr>
</tbody>
</table>

Fig. 5. Photos of the various flow patterns: (a) cap flow, (b) slug flow, (c) elongated Taylor bubble flow, (d) churn flow, (e) annular flow.
The probe design is similar to that proposed by Costigan and Whalley [1997] and Ma et al. [1991]: it is made up by a pair of measuring half rings (span of the arc $\beta = 90^\circ$) facing one another with guard electrodes (again half-rings) maintained at the potential of the corresponding measuring electrodes. All the electrodes have the section diameter of 0.6 mm and the guards are separated by the distance of 1 mm from the measuring ones (see Fig. 3). It is worth noting that this kind of electrode design allows the observation of two phase phenomena on a transversal pipe section, ensuring higher spatial resolution than that obtained by other geometries [Andreussi et al., 1988; Tsochatzidis et al., 1992].

The calibration of the resistive sensor has been performed by comparing the instantaneous void fraction measured by the sensor with the local diameter of the bubble as estimated in pictures taken by means of a high resolution camera. In this way each piece of the signal describing the passage of a bubble has been correlated with the fraction of air occupying the tube section. The calibration curve reported in Fig. 4 has been obtained as the seventh order polynomial curve interpolating the estimated void fraction for several bubbles.

### 2.2. Experimental tests

Once the sensor has been characterized, an experimental campaign has been performed.

In order to investigate on the constitution of various types of flow patterns, a series of tests has been carried out by varying the two-phase mass flow rates.

Table 1 shows the various operating conditions of the performed tests. Under these conditions different flow patterns are established in the pipe. The general trends of the distribution of the two phases for the various flow patterns is shown in Fig. 5.

In particular, the following correspondence between operating conditions and typical flow patterns has been observed during the experimental tests:

- $Q_{\text{Water}} = 9.961/l\text{ min}, Q_{\text{Air}} = 0.81/l\text{ min} \to \text{Cap}$
- $Q_{\text{Water}} = 2.401/l\text{ min}, Q_{\text{Air}} = 11/l\text{ min} \to \text{Slug}$
- $Q_{\text{Water}} = 2.401/l\text{ min}, Q_{\text{Air}} = 101/l\text{ min} \to \text{Elongated Taylor bubble}$
- $Q_{\text{Water}} = 3.061/l\text{ min}, Q_{\text{Air}} = 401/l\text{ min} \to \text{Churn}$
- $Q_{\text{Water}} = 1.51/l\text{ min}, Q_{\text{Air}} = 1151/l\text{ min} \to \text{Annular}$

The analyses reported in the following section will be restricted only to these flow patterns, assumed as representative of typical flow patterns reported in literature [Costigan & Whalley, 1997].

### 3. Time Series Analyses

Figure 6 reports the experimental void fraction time series detected during the experimental operating conditions described above. It is worth noting that the experimental time series do not seem to be periodic; in fact, it is possible to observe that great amplitude and frequency differences occur between consecutive oscillations. At the same time, the phenomenon is clearly dominated by the existence of complex but recurrent behaviors, as the repetition of similar (but not identical) waveforms demonstrates.

The study of the experimental time series in the time domain has pointed out the opportunity to analyze their behavior also in the frequency domain. Figure 7 reports the power spectral density distribution of the same time series described in Fig. 6. In this plot it is possible to observe how the complexity that characterizes the time series poses a limit to the validity of Fourier analysis; nonetheless some interesting considerations can be drawn as a preliminary approach to the problem. In particular, the phenomenon is clearly characterized by a broad-band power spectrum. This means that it is not possible to characterize the system dynamics by choosing specific frequency values because the whole frequency range is excited. In other words, the nature of the phenomenon is either stochastic or strongly characterized by a nonlinear deterministic source of the dynamics, which cannot be exploited by means of linear time series analysis techniques.

The last option seems to be confirmed by the existence of a strong autocorrelation in the time series, which is described in Fig. 8. In fact, stochastic phenomena are typically uncorrelated and, therefore, present a flat autocorrelation function (equal to 1 spike at time sample zero and approximately 0 elsewhere), whereas time series from deterministic phenomena may show marked autocorrelation, at least if appropriate time windows are chosen. From the analysis of the plots in Fig. 8 it is apparent that for all kinds of flow patterns it is possible to select appropriate windows of observation where the void fraction time series is characterized by relevant autocorrelation. It is worth noting that not all of the possible windows
Fig. 6. Void fraction time series: (a) cap flow ($Q_{\text{air}} = 0.81/\text{min, } Q_{\text{water}} = 9.961/\text{min}$), (b) slug flow ($Q_{\text{air}} = 11/\text{min, } Q_{\text{water}} = 2.401/\text{min}$), (c) elongated Taylor bubble flow ($Q_{\text{air}} = 101/\text{min, } Q_{\text{water}} = 2.401/\text{min}$), (d) churn flow ($Q_{\text{air}} = 401/\text{min, } Q_{\text{water}} = 3.061/\text{min}$), (e) annular flow ($Q_{\text{air}} = 1151/\text{min, } Q_{\text{water}} = 1.501/\text{min}$).
Fig. 7. Void fraction power spectrum (a) cap flow, (b) slug flow, (c) elongated Taylor bubble flow, (d) churn flow, (e) annular flow.
are appropriate to point out autocorrelation in the time series and the window choice is indeed arbitrary. This, again, confirms the inadequacy of linear tools, such as autocorrelation analysis, to deal with the complexity of the dynamics of two-phase flows.

In order to exploit determinism in the system, the attractors of the experimental conditions have been reported in Figs. 9–11. Even a basic morphological analysis of this plot, points out the existence of a well-defined structure, which represents a first important hint of chaotic behavior. Deeper analytical investigation of chaos in the system in study is beyond the scope of this preliminary study. In this context, it is interesting to observe that the recurrent behavior mentioned in the analysis of the time series in time domain is expressed in phase space by the regular structure of the attractors. In particular, the attractors of cap flow, are characterized by a distribution of trajectories in sufficiently separated bands (as Fig. 9(b) shows). This
Fig. 9. (a) Cap flow experimental attractor; (b) particular of trajectory distribution.

Fig. 10. Experimental attractors: (a) slug flow, (b) elongated Taylor bubble flow.

Fig. 11. Experimental attractors: (a) churn flow, (b) annular flow.
is a strong indication of fractal nature that may point out the existence of chaos in the system.

Another consideration can be drawn observing the attractors of cap, slug and elongated Taylor bubble flows in Figs. 9 and 10. As mentioned in the introduction, these flow patterns belong to the same general class and are, in fact, often classified together [Mi et al., 1998]. On the other hand, their phase space representations are characterized by relevant differences in the attractor morphology. As an example it is possible to observe how the phase space region occupied in the cap flow, by the mentioned fractal distribution of trajectories seems to be prohibited to trajectories for the case of slug flow, except for the external contour of the cap flow attractor, which becomes the lower limit of the relatively stable trapping region of the bubble flow attractor. In the elongated Taylor bubble flow the stability of this region is progressively compromised under the influence of oscillations of the liquid film. A further change can be observed in Fig. 11 for the churn and annular flows where a new basin of attraction arises in the upper part of phase space. This basin of attraction is evident for the annular flow, whereas for the churn flow it coexists (and is predominant) with that of the whole class of slug flow types.

Previous morphological considerations show that a series of bifurcations occurs and can be exploited in phase space in order to identify the various flow patterns.

4. Conclusions

An experimental apparatus has been built and tested in order to study the dynamics of two-phase flow in vertical pipes. The present study reports the description of the void fraction sensor appositely constructed and the procedure used for its calibration.

A preliminary analysis of the time series shows the inadequacy of classical linear tools for time series analysis, but seems to point out the existence of a deterministic source of the dynamics. The last observation is confirmed by both the recurrent behavior observed in time domain and the regular structure of the attractors in phase space. These preliminary results point out the opportunity to adopt nonlinear tools based on phase space analysis for appropriate characterization of the dynamics of two-phase flows.

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References


