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Brief communication

Flow pattern identification in gas–liquid flows by means of phase density imaging

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1. Introduction

The widespread diffusion of two-phase flows, which may be encountered in a large number of applications ranging from oil extraction and transport to power generation, chemical plants and many other industrial processes, assigns a great importance to a deep understanding of their behavior. From the first phenomenological investigations, the complete theoretical modelling of such flows has nowadays reached a high level of completeness and maturity (Ishii and Hibiki, 2006). Regrettably the analytical solution of the resulting equations is impossible and at present numerical solution is not really viable for real-world industrial flows, despite the relevant progresses in this field (Lahey, 2009; Scardovelli and Zaleski, 1999; Tryggvason et al., 2001; Fuster et al., 2009; Horgue et al., 2012, 2002). The quantitative analysis of the local flow structure, in terms of void fraction (or holdup for liquid–liquid flows) and particularly of interfacial area concentration, still requires experimental investigations and is strongly dependent on the distribution of the phases, the so-called flow pattern. The latter also has important effects from both the mechanical and thermal points of view, e.g., the sudden increase in the pressure drop due to the transition from the annular to the stratified flow pattern in water-lubricated oil pipelines or the burnout for heat transfer at fixed power. Consequently, many studies have been devoted to the prediction of the flow pattern, from the pioneering works (Jones and Zuber, 1975) to very recent investigations (Paranjape et al., 2012; Ameel et al., 2012) and using techniques which spans from direct visual observation to very sophisticated techniques that are capable of offering a 3D reconstruction of the flow structure: multiple local probes (Sekoguchi and Mori, 1997; Pietruske and Prasser, 2007; Hampel et al., 2009; Pereza et al., 2010), γ-ray, X-ray, impedance or ultrasound tomography (Tjugum et al., 2002; Bieberle et al., 2010; Pietruske and Prasser, 2007; Xu and Xu, 1997), magnetic resonance imaging (Daidzic et al., 2005). Between these two extremes, various techniques with different levels of sophistication have been proposed, that rely on searching a correlation between the flow pattern and the values or distributions of some indicator variables (Jones and Zuber, 1975; Nguyen et al., 2010; Elperin and Klochko, 2002; Lynch and Thurow, 2009; Annunziato and Abarbanel, 1999; Lee et al., 2008; Rosa et al., 2010; Xu and Xu, 1997; Zhang et al., 2010; Paranjape et al., 2012; Ameel et al., 2012). Apart from the most complex approaches, the main limitation of these techniques is the difficulty in obtaining a clear distinction between partially similar flow patterns, e.g., plug and slug flow. In this paper a technique is proposed that is able to visualize local information about the flow structure (even if it cannot offer any measurement of the interfacial area concentration) starting from simple acquisitions of the phase density function and which is also able to evidence very well the differences between flow patterns, both directly and by means of some derived quantities.

2. The phase density function

The most used local instantaneous quantity for the description of the flow structure is the phase density function $\delta(\vec{p}, \tau)$, which is

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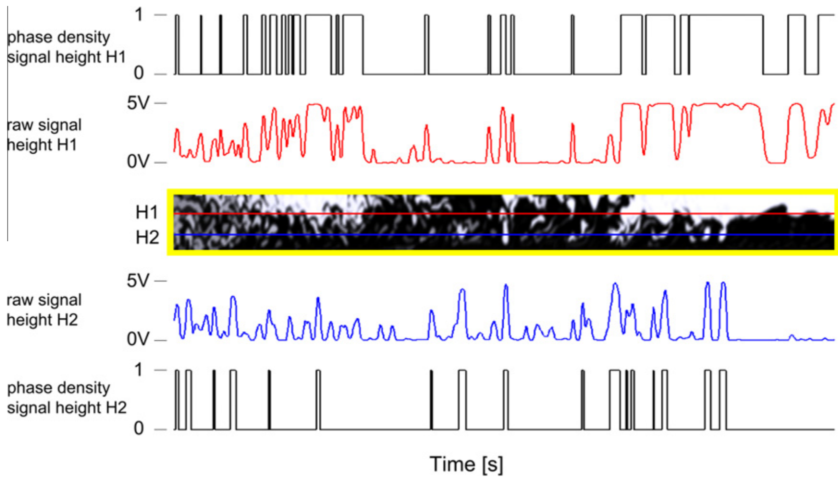

Fig. 1. Sketches showing two examples of phase density signals sampled from a simulated two-phase flow (black is water, white is air) at two different heights $H1$ and $H2$ along the vertical section of the duct. Raw signals (red and blue) and corresponding single-threshold filtered signals (black) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

also called state density function (Ishii and Hibiki, 2006) and which will be the main subject of this work. It can be defined as follows:

$$\delta(\vec{p},\tau)\begin{cases} = 1 & \text{if at instant } \tau \text{ point } \vec{p} \text{ is immersed in the gaseous phase} \\ = 0 & \text{if at instant } \tau \text{ point } \vec{p} \text{ is immersed in the liquid phase} \end{cases}$$

The phase density function can be sampled by means of local optical or impedance probes. Different types of probes may be designed. Details about such measurement devices, including the known problems and limitations they are affected by, can be found in (Barrau et al., 1999; Cartellier, 1999; Barrau and Cartellier, 1998; Julia et al., 2005; Kim et al., 2000) for optical probes and in (Teyssedou et al., 1988; Vince et al., 1981; Sekoguchi and Mori, 1997; Pietruske and Prasser, 2007; Hampel et al., 2009; Pereza et al., 2010) for impedance probes. These issues do not affect the concepts and analyses presented in this work, so they will not be discussed here. Data shown in the following sections were acquired using single-tip impedance probes, whose operating principle is described hereafter. One phase (water) has to be conductive, the other (air) insulating. A thin conductive stem, completely insulated except for the tip, is immersed in the flow. The sensing tip is placed in the point of interest, while a second electrode is immersed in the flow near the bottom of the duct, to be – for horizontal flows – always covered by water. When the measuring tip is immersed in water too, the circuit is closed and the difference of potential between the probe and the reference electrode goes to "zero". Otherwise, the circuit is open and a higher difference of potential is present between the two electrodes. Therefore, sampling the difference of potential 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. Fig. 1 shows a sketch of two phase density signals sampled from a two-phase flow (black is water, white is air) at two different heights $H1$ and $H2$ along the vertical section of the duct. Raw signals and corresponding filtered (single-threshold) signals are shown. The depicted flow was simulated using a Volume-Of-Fluid approach, which produces cells with volume fractions between 0 and 1, with the *interFoam* solver of the OpenFOAM® open source CFD toolbox (OpenFOAM, 2011) (version 1.7.1). The flows in Figs. 3 and 7 were simulated in the same way too. No validation has been performed up to now on the proposed results, so they should be considered purely for qualitative purposes.

3. Experimental set-up and investigated flow regimes

The experimental acquisitions were taken on the plant (Fig. 2) which is available at the Multiphase Thermo-Fluid Dynamics Laboratory, Department of Energy, Politecnico di Milano. It consists of a closed loop for the liquid phase (water) and an open loop for the gaseous phase (air), sharing a stretch where the two-phase flow sets up. Such test section is approximately 12 m long and it is made of Plexiglas®, to allow visual and photographic observation of the flow. A detailed description of the experimental set-up can be found in Arosio and Guilizzoni (2006) and Arosio and Guilizzoni (2008).

On the test section, local – optical or impedance – probes can be placed, to sample the phase density function in each point of interest, along with the scheme presented in Fig. 3. For each chosen cross-section, an adequate mesh of experimental points has to be acquired to ba able to calculate cross-section averaged values of the quantities. Using single-tip local probes, this can be obtained by performing many acquisitions, each time positioning the probe tip in a different point on the chosen cross-section. A grid was selected which is uniformly spaced in polar coordinates (i.e., the points correspond to a rectangular grid on a Cartesian plane with radius from the duct axis and angle from the vertical direction as coordinates). Such choice gives the opportunity to have repeated measurements in the center of the cross-section (with consequent direct verification of the repeatability of the measurements), even if it implies a crowding of the points near the duct axis. The investigated flows may be approximated as symmetric across the vertical plane parallel to the duct axis, therefore five diameters were investigated, with an inclination from the vertical axis ranging from 0° to 80°. Nineteen points were sequentially acquired along each diameter, spaced $D/20$ from each other. As the measurements are not simultaneous, repeatability issues have to be considered: previous analyses shown that the average absolute deviation between repeated measurements (including plant stop& restart, flow rates re-setting and probe re-positioning) of the local void fraction is 2.12 and the standard deviation of the absolute percentage error is 1.21 (Arosio and Guilizzoni, 2006).

Flow conditions range from 2.0 to 6.0 kg/s in terms of mass flow rates $\dot{m}_L$, with inlet (i.e., evaluated using the pressure at the mixing