Metrological concerns in multiphase flow measurement

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Abstract. This work presents partial result of an introductory investigation on parameters of influence for the multiphase flow measurement reliability, which is going on in the Brazilian National Metrology Institute - Inmetro. Studies were performed with air-water mixture flowing inside a horizontal pipe. The flow pattern map of the experimental bench is identified, and parameters that influence for the flow pattern formation are analysed. Paper aims to disseminate knowledge on metrological bias on multiphase flow measurement. A brief overview on this theme is presented, along with the latest results of this research line at Inmetro.

1. Introduction

Static and dynamic fluid measurements play an important role in industrial, environmental, safety, medical, aerospace processes, among others. Moreover, metrological requirements are in increasing need for modern industrial solutions that assure exact measurements involving a wide range in volume, and the need for continuous or stepped sampling collection. Examples are the quantities of fluid that must be controlled in pharmaceutical and biological processing, or that one dealt in the oil and gas industry, as well as those related to environment pollutant monitoring, [1-2]. Nevertheless, regardless of the application, reliability of the measurement results is a must demanded.

The reliability in multiphase flow measurement has been receiving increasing attention in the last decades, and it has been driven by industrial demands and also by the need for sustainability. Important progress has been observed in this field, however, as the dynamics of the physical processes present in multiphase flow are very intricate, the metrological community has been facing significant challenges while pursuing to provide confidence in the measurement of this type of flow.

The metrological traceability chain for evaluating flowmeters to be employed in the measurement of so complex flow and also for evaluating the systems where these meters could be calibrated, claim for substantial advances on better understanding of the phenomena. Thus, aiming to contribute to this field, the Brazilian National Institute of Metrology, Quality and Technology - Inmetro has introduced in its activities the research line on multiphase flow measurement.
Until the authors of the present article could search, scarce works in the literature are focused in discussing metrological concerns on multiphase flow measurement. So, the goal of this work is to contribute for knowledge dissemination about metrological bias related to multiphase flow measurement, by presenting a brief overview of the main consensuses on this theme, and also showing the lessons learned by the authors during the process of studying mixtures of liquid-gas flowing inside horizontal pipes.

2. General parameters which influence the uncertainty level and reliability of a multiphase flow measurement

Although advances of technology has been also motivated by interests on better understanding of the multiphase flow behavior, it is known that the complexity inherent to the physics of this flow and fluid characteristics influence the limits for using such technologies. Succinctly, the measurement result of a multiphase flow will depend on parameters as: i) the flow behavior (flow pattern, phase regime, instabilities, flow direction etc.); ii) phase properties (surface tension, viscosity, density, electrical and thermal conductivity, salinity etc.); iii) flow condition (emulsion, water cut, sediment, homogeneity, temperature, pressure, time dependency, stability etc.); iv) flow region (ex. geometry, scale, pipe material and roughness etc.); v) facility characteristics and associated boundary conditions (vibration level, connections, straight length, rigidity, temperature of the solid surfaces in contact with the fluid etc.); vi) environmental conditions; vii) instrument, technology and technique of measurement (dimensions, operation principle, equipment material, data rate, nominal range etc.), among others. Some of these parameters are usually correlated in the solution of equations involving multiphase flow.

A reliable quantification of a multiphase flow (i.e., totalized volume during a time interval, flowrate and velocity of each phase) can be strongly affected by several of those cited parameters, thus, the establishment of standardization for providing metrological traceability will request a compromise between technologies, metrological traceability of all involved quantities and the possibility of controlling and monitoring the flow.

In the specific case of multiphase meters, there are currently several commercially available models based on different measurement principles, and for each one a mathematical model is necessary to convert readings to flow patterns [3]. So, if the flow pattern is misinterpreted, all related quantities will not be reliable. This fact makes clear the need for better investigation of the effects on the propagation of measurement errors.

3. Aspects considered in the study of the two-phase flow in horizontal pipe

Aiming to understand how to get accuracy and reliability when using multiphase flowmeters, experimental investigations on two-phase flow were chosen as starting point in this direction. Two central questions have oriented the investigations:

- How to ensure the metrological traceability?
- What parameters must be reproduced in a laboratory bench, in order to create calibration conditions which would represent the field operating conditions of a multiphase meter?

To reach the goals, the first step was the construction and characterization of a horizontal bench. The two-phase flow patterns and other parameters for the available operating conditions were also analyzed as a way of creating repeatability conditions necessary for the execution of future tests.

The optical technique Shadow Sizer [4] was initially used to identify the flow patterns. This technique consists of a high resolution camera and a source of light, positioned in opposite one to other. The shadow of the particles (bubbles, for example) present in the flow is captured, and the diameter, area, perimeter and velocity of the bubbles can be identified after processing the images captured by the camera. Table 1 summarizes the characteristics of the bench and the main specifications.
Table 1. Test bench characteristics.

| Description                                                      | Specification                  |
|-----------------------------------------------------------------|--------------------------------|
| Total length of the flow visualization field (acrylic piping)    | 10.3 m                         |
| Internal nominal diameters of acrylic pipes (D)                  | 19 mm e 44 mm                  |
| Maximum liquid and air flowrates in 25 mm piping                 | 20 L/min and 40 L/min, respectively |
| Maximum liquid and air flowrates in 50 mm piping                 | 250 L/min and 60 L/min, respectively |
| Inner diameter of each air distributor valve injector            | 5 mm                           |

In the bench, filtered water flows from the reservoir to the piping. Water flowrate is monitored by calibrated electromagnetic flowmeters, and the range is established by a valve and a hydraulic pump (controlled by frequency inverter). Compressed air is injected in the line through diametrically opposed four-way distributor valve. Calibrated thermal mass flowmeters monitor the air flowrate in each valve. Figure 1 shows a view of the bench. In the present study, the discussions were based on the flow inside the piping of 44 mm internal diameter.

4. Experimental procedure and results

Firstly, the mapping [5] of occurrence of two-phase flow patterns in the 50 mm piping was detailed, on which is indicated the water and air supply limits of the bench. Figure 2 shows such map.

Conditions of the two-phase flow characterization:

- Ambient temperature: 23 °C to 26 °C;
- Humidity: 62 % to 80 %;
- Ambient pressure: 1007 hPa to 1017 hPa;
- Liquid temperature: 25 °C to 31 °C;
- Gas temperature: 20 °C to 22 °C;
- Range of air pressure at the pipe inlet: from 39.2 kPa to 147 kPa.

Based on this map, after running some tests in the bench, for analyses were selected experiments considering the cases listed on Table 2, with some gas and liquid flowrates not indicated on the map. In such experiments, while maintaining the mean water flowrate value around 56 L/min, and then varying both the mean air flowrate and the air injection distribution at the tube entrance, the flow behavior at the
tube entrance region and the established two-phase flow pattern far from the tube entry were observed. Air was injected at the tube entrance through two valves which were vertically aligned with each other (numbered 1 and 2, for north and south positions, respectively) and crossing the symmetry axis of the piping. The frequency level of the hydraulic pump motor was maintained, but the resulting water flowrate showed fluctuations in each case due to changes in the internal piping pressure promoted by changes in the amount of injected air flowrate. The acrylic tube of the bench can resist to internal pressure up to 0.26 MPa.

| Case | Liquid flowrate (L/min) | Gas flowrate (L/min) |
|------|-------------------------|----------------------|
|      |                         | Injector 1 (north)  |
| 1    | 56.4                    | 10.9                |
| 2    | 56.6                    | 10.7                |
| 3    | 56.5                    | 10.8                |
| 4    | 57.4                    | 10.9                |
| 5    | 58.5                    | 10.55               |
| 6    | 57.4                    | 6.28                |
| 7    | 56.4                    | 1.52                |

Influences due to different air injection mode, considering a same air-water flowrate ratio, could be discussed by comparing case 2 with case 7, and case 4 with case 6. The following figures show the captured images through the Shadow Sizer system.
Figure 3. (a) Case 1 (b) Case 2 (c) Case 7 (d) Case 4 (e) Case 6 (two frames) (f) Case 5 (two frames).

Case 5 is depicted on Figure 8, on which can be identified the effect, to the flow behavior at the entrance region, of the increment in air flowrate when the amount of air injected through south is greater than that one injected through north.

Table 3 indicates the two-phase flow pattern established far from the tube entrance for each case, and associated comments.

Table 3. Established two phase flow (approximately 5 meters away from pipe entrance).

| Case | Flow pattern | Comments |
|------|--------------|----------|
| 1    | semi-slug    | plug<sup>a</sup> |
| 2    | plug         | well defined plug<sup>b</sup> |
| 3    | plug         | well defined plug<sup>b</sup> |
| 4    | plug         | well defined plug<sup>b</sup> |
| 5    | plug         | plug (predominant)<sup>b</sup> |
| 6    | plug         | almost slug<sup>a</sup> |
| 7    | slug         | almost semi-slug<sup>b</sup> |

<sup>a</sup> near air injection point.
<sup>b</sup> 5m far from pipe entrance.

5. Discussion

Among the several cases listed on Table 2, the most representative are those depicted on Figures 3 to 8. From Figures 3 and 4 it can be noticed the similarity of the flow appearance of cases 1 and 2 near the air injection point. However, although the mean air flowrate injection by south in case 1 is about 5 times less than that in case 2, in case 1 the flow pattern built up near the air injection point was plug, but the established flow pattern at 5 meters far from the entrance was semi-slug. The semi-slug pattern which was identified was very instable, marking a transitional condition of the flow behavior in that pipe position. In case 2, very close to the air injection point the plug pattern was already defined. Otherwise, just after the air injection point, in both cases the characteristics of the gas phase due to north air injection were similar, i.e., the gas bubbles generated by the air inserted through south injector did not separate the upper gas layer (it was observed a wavy flow kind at this region of the pipe, as shown on Figure 4, but the wavy flow characteristic was changed at the point where the bubbles touched the upper air layer, then developing the plug pattern).

In case 7, the air flowrates inserted through south and north were inverted in relation to case 2. Figure 5 shows the resulting effect on the flow characteristics just after the air injection point. As indicated on Table 3, the flow pattern built up close to air injection position was almost semi-slug, while 5 meters away this point the flow pattern was slug.

An equivalent comparison was made between cases 4 and 6 (Figures 6 and 7), but in these cases the lower air injection flowrate was four times higher than that one of case 2. In these cases, as seen on
Table 3, the flow pattern far from the air injection point were similar (plug), but in case 6 the plug flow was weakly outlined (trending to slug), showing that in such tube position the flow pattern probably was going to transition. At the air injection region, while in case 4 the liquid surface was wavy (Figure 6), in case 6 large air bubbles reach the water surface and disturbed the wavy profile in that point (see the two frames on Figure 7), then provoking the plug flow formation since this piping position. Figure 8 (case 5) also shows the changes of the upper air layer at the air injection region.

So, based on the cases observed up to here, an interesting finding by comparing mainly the cases 2 and 7, 4 and 6, is that, for some air and water flowrate ratios, the mode of air injection could influence the two-phase flow pattern formed inside the tube, even up to large distance after the air injection point (in this study, the position of visualization was 5 m, i. e., about 100D).

6. Conclusion
With the aim of getting elucidations on how to deal with some parameters which impacts on multiphase flow measurement reliability, experiments involving two-phase flow were conducted in a horizontal pipe. The flow mapping for the two-phase flow was pursued, and five flow patterns were developed inside the pipe of diameter 50 mm. It was observed that depending on the air-water flowrate ratio it can occur repeatability of the flow pattern at a same position far from the pipe entrance. In addition, when considering a same air-water flowrate ratio, within the range of air flowrate tested, the results indicated a tendency of the mode of air injection to influence the flow pattern characteristics at a fixed position far from the tube entrance. Besides, it was possible to verify that the wavy pattern generated upstream the air injection point was influenced by size, rotation and buoyancy of the air bubble injected at the lower part of the pipe. However, more investigation about such influences must be done in order to clarify several aspects of the flow behavior. In the continuity of this research other parameters for discussion should be included, such as variables of influence which must be monitored in a better way, as is the case of the liquid temperature increasing due to pumping. In fact, all these findings indicate the need to carry out multiphase flow measurements with a metrological approach, and those aspects will be investigated in the near future.

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