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THREE-PHASE OIL-WATER-GAS FLOW TOMOGRAPHY BY WIRE-MESH SENSOR

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Abstract. *In this work an algorithm for three-dimensional qualitative reconstruction of bubbles in three-phase flows that allows the flow visualization in a pipeline is presented, and therefore being a very useful tool for the study of fluid mechanics and the optimization of industrial processes in which multiphase flows occur. The algorithm was applied at experimental points obtained in an experimental campaign using oil, water and air as working fluids. The data were collected with a fast response impedance sensor with 16x16 wires in a vertical glass pipe with a total length of 12 m and 0.05 m i.d..*

Keywords: *wire-mesh sensor, flow tomography, three-phase flow.*

1. INTRODUCTION

Multiphase flow is the definition given to a simultaneous flow of at least two physically distinct and immiscible substances (called phases) and the variety of spatial distribution of phases generates the flow pattern or regime (Dos Santos et al., 2005) (Da Silva, 2008). The lack of a consolidated characterization of these patterns makes it difficult to obtain quantitative parameters and flow visualization, which are relevant to the efficiency and safety of processes involving multiphase flows regarding the equipment and plants used (Dos Santos et al., 2005) (Da Silva, 2008).

A better understanding of the phenomena regarding flows in petroleum industry, for example, would make it possible to optimize the use of this non-renewable source of energy and could also reduce production costs of its derivatives (Pena, 2015).

Non-intrusive tomography techniques to obtain physical parameters of multiphase flows are advantageous in the flow study since they do not affect or disturb it (Santos et al., 2018), but their main disadvantages are low temporal resolution (x-ray and gamma tomography) or low spatial resolution (electrical or ultrasound tomography), high cost (Santos et al., 2015) (Santos, 2011) (Prasser, 1998) (Da Silva et al., 2010) and the need to solve an inverse problem (Roitberg et al., 2008).

The wire-mesh sensor (WMS) is an intrusive tomography technique whose major disadvantages are: the flow disturbance downstream the sensor (Roitberg et al., 2008) (Zhang et al., 2013) and its moderate spatial resolution (Pena, 2015), although these characteristics are offset by the ability to perform direct measurements on flow (Roitberg et al., 2008); low cost and high temporal resolution (Da Silva et al., 2007) (Da Silva, 2008) (Zhang et al., 2013) and it is an effective method for obtaining hydrodynamic data of flow (Roitberg et al., 2008), without requiring reverse flow reconstruction (Roitberg et al., 2008) (Pena, 2015).

The main goal of this research was to develop an algorithm and a MATLAB™ code for the treatment and analysis of the data obtained through the fast response impedance sensor of the Industrial Multiphase Flow Laboratory (LEMI) in order to generate three-dimensional tomographic images of the three-phase oil-water-air flow observed in the laboratory.

Due to the great importance of flow regimes characterization (Dos Santos et al., 2005) (Da Silva, 2008) and to the advantages of the wire-mesh sensor (Da Silva, 2008) (Roitberg et al., 2008) (Da Silva et al., 2007), this work sought to contribute to the study of the sensor utilization by aiming to implement qualitative tomographic imaging in the fundamental routine of the wire-mesh sensor data analysis algorithm.

2. MATERIALS AND METHODS

2.1 Experimental setup

The experimental apparatus that originated the data consists of a vertical glass pipeline with a total length of 12 m and 0.05 m of diameter. At its inlet water, viscous oil and compressed air were injected. Each of the individual fluids had its flow rate measured to obtain different flow patterns. The test section, which starts at 120 diameters away from the fluids injection point, featured thermocouples, differential and absolute pressure gauges, wire-mesh sensor and high-speed camera with transparent pipe and visualization box (Fig. 1).

The WMS (Fig. 1) has two wire planes, spaced by 1 mm, with 16 electrodes with 0.1 mm diameter each. The wires are equally spaced by 3.0 mm, sweeping the internal pipe diameter of 50 mm. The sensor was developed in LEMI, being a home-made prototype (Pena, 2015).The visualization box has a length of 58 mm in one half and 57 mm in the other one and it was made of acrylic so that it was possible to obtain images, in synchrony with the sensor, with a high-speed camera (Olympus i-Speed 3 monochrome) whose acquisition rate is between 1000 and 2500 frames per second.

For each measurement, the wire-mesh sensor produces an $\mathbf{M}_{16x16}$ array with the electrical permittivity values of the fluid measured by the electrodes in the transverse plane of the pipeline, resulting in a flow frame or slice. At the end of the measurement, the $\mathbf{M}_{(i,j,k)}$ matrix is obtained, where *i* and *j* address the electrode crossing point areas and *k* indicates the frame (Fig. 2) (Santos et al., 2014) (Mukin, 2016). Since the values collected by the electrodes are complex impedances, it is necessary to mathematically manipulate them with the relationship models for three-phase flows in order to transform electrical permittivity into phase volumetric fraction (Pena, 2015).

The data used in this work are part of the results of previous researches conducted by LEMI and they are measurements made by the WMS of a water-dominated flow with air Taylor bubbles and scattered oil bubbles pattern.

Figure 1. Home-made wire-mesh sensor prototype developed in LEMI and acrylic box for its installation in the pipe (Pena, 2015).

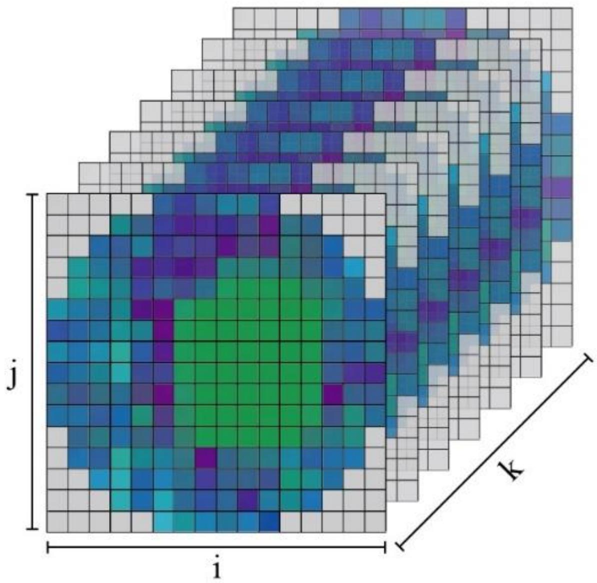

Figure 2. Matrix $\mathbf{M}_{(i,j,k)}$ representation with different permittivity values in different colors.

2.2 MATLAB code

The algorithm used in this research can be divided into four parts: data allocation, data treatment, mathematical manipulation and flow reconstruction (Fig. 3). The main routine purpose is to generate images of the multiphase flow from its electrical permittivity matrices obtained by the WMS, and it works according to the following script:

I. Allocation of the complex electrical permittivity values of each cross plane read by the WMS to a matrix;

II. Assignment of weight coefficients for the **M** matrix cells according to their location within the pipe, having values for partial or total contribution to the mathematical data manipulation, which depends on where the crossing point is located. Crossing points closer to the pipe wall have smaller values than the ones at the pipe center (Fig. 4);

III. **M** matrix values calibration using sensor data for the least and the most permissive single-phase fluid in the multiphase flow (Santos et al., 2018), so that no value of **M** is less than zero or greater than 1;

IV. Data correction to represent only the area inside the pipe, thus the pipe wall and its outer area are represented by grey as seen in Fig. 2 and Fig. 5;

V. Utilization of mathematical models available in the literature (Pena, 2015) for the relationship between measured complex permittivity and volumetric fraction of a phase in order to calculate phase fractions. In the example of Figure 7 and Figure 8, the method used is the Bruggeman model (Eq. 1) and its detail can be found in Pena, 2015;

$$\Sigma_{n=1}^{N} \alpha_n \cdot [(\varepsilon_n - \varepsilon_x) \div (\varepsilon_n - 2\varepsilon_x)] = 0 \qquad (1)$$

VI. Imaging the longitudinal and cross section of the flow by assigning color to each pixel according to each fluid phase fraction value in that area.

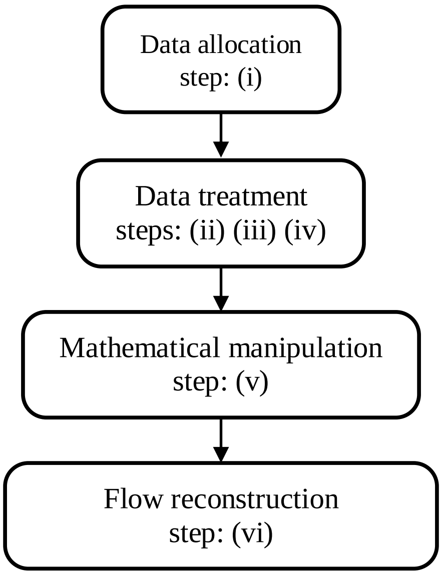

Figure 3. Algorithm flow diagram.

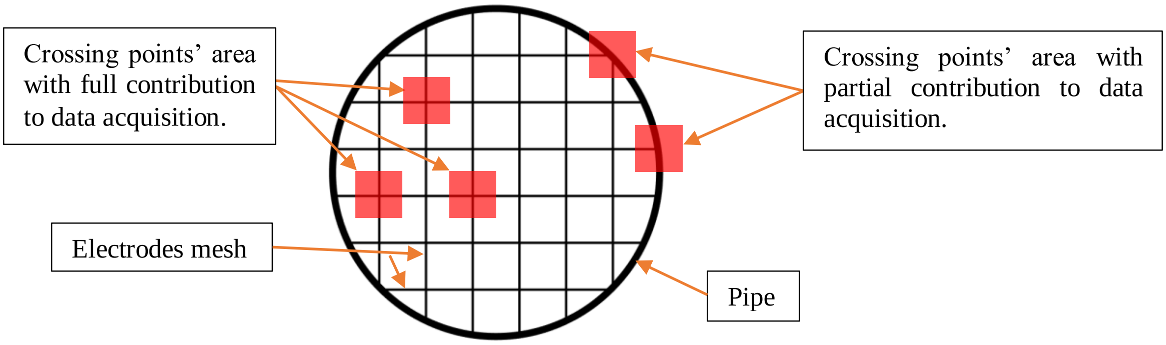

Figure 4. Demonstration of a generic electrode mesh sensor in the pipeline, showing the difference in contribution to data acquisition between a peripheral crossing point (partial values) and a central point (full values).

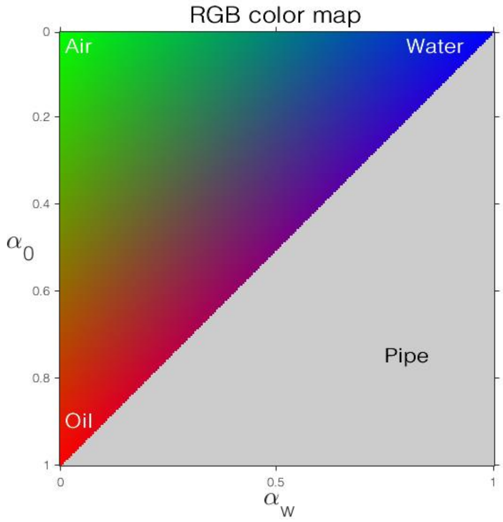

Figure 5. RGB color map used for flow reconstruction and its phases fractions. The pipe wall and its outside are represented in grey, water in blue, air in green and oil in red and the sum of the colors represents phase mixtures.

The implementation done in the routine is a qualitative three-dimensional reconstruction, instead of just two-dimensional images (flow longitudinal and cross sections). For this, the *vol3d.m* (Woodford, 2020) function available on the MathWorks® online platform was used and the water, air and oil phases were assigned the colors blue, green and red in RGB format, respectively, and phase mixtures are represented by the nuances between the colors (Fig. 5).

3. RESULTS

In Figure 6 there are 3 frames taken from the filming of the Taylor's bubble passing through the viewing box. The video is also part of LEMI's database and it was made by the PhD student Carlos Marlon Santos. In those images it is possible to see the bubble's nose and tail immediately before passing through the wire-mesh sensor plane and the overall bubble silhouette. In Figure 7 there is the longitudinal image of the same bubble that was reconstructed by the original algorithm and the one with *vold3d.m* routine implementation seen by a diametrical cut.

It is noted that both processes not only reconstruct the bubble silhouette better than the shape that can be obtained by the high-speed camera, but they also indicate the phase fractions at each point of the flow section according to the pixel color (Fig. 5). However, there is a loss of detail in the diametrical cut of the bubble generated by the new algorithm. It is indicated in Fig. 7b that the bubble nose is located below the height of the bubble reconstructed with the original MATLAB code. In addition, the bubble has lost width and contour definition, causing its shape to lose definition and detail in several pixels.

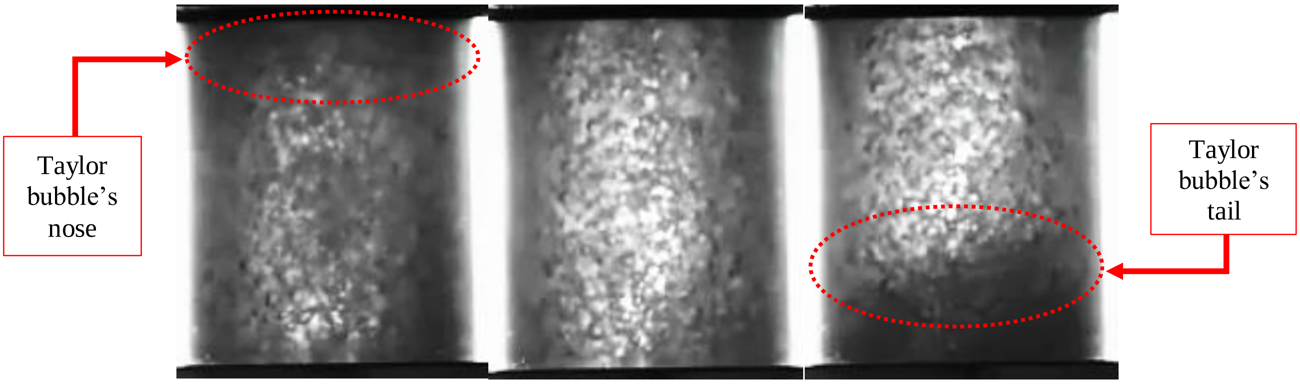

Figure 6. Sequenced images of the Taylor bubble passing through the visualization box. The images were taken from the video of the three-phase flow done by the PhD student Carlos Marlon Santos. The bubble's nose and tail are indicated in the first and last picture respectively.

This may mean that during the interpolation of data to generate flow volume as a whole, there is suppression of values, which affects the deduction of quantitative parameters of the flow such as the bubble shape and size. Even so, the image generated by the new code is more detailed than the pictures taken from the high-speed camera video, since the outline is better defined and, if analyzed from an infrastructure aspect, the sensor does not require a transparent box with adequate lighting for data acquisition, in addition to that the WMS measurements indicate phase fraction values for mixtures with colors, not depending on the contrast and brightness of the picture.

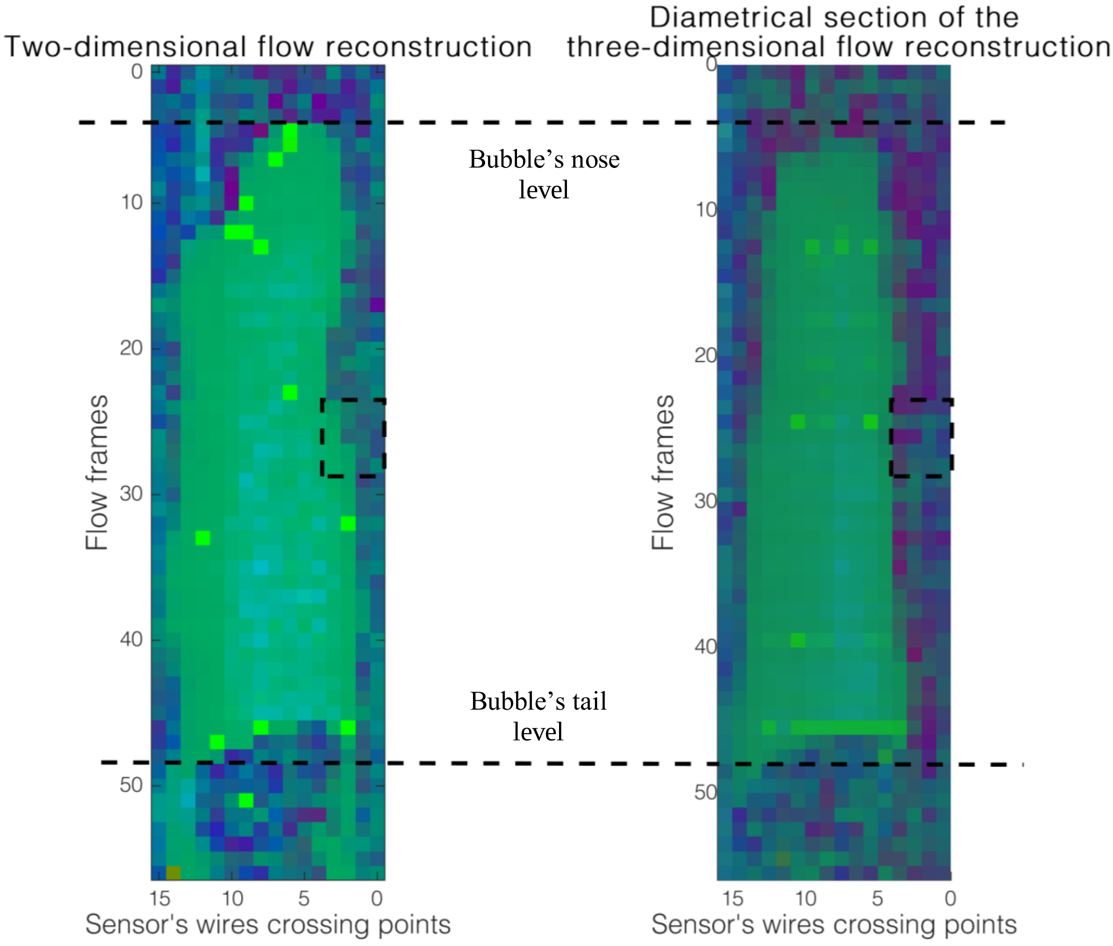

Figure 7. Longitudinal view of the Taylor bubble reconstruction in a water-air-oil flow using the Bruggeman relationship model. In (a) there is the image made by the two-dimensional reconstruction code and (b) shows a diametrical cut of the volume made by three-dimensional flow reconstruction routine.

Figure 8 shows the three-dimensional reconstruction of the same part of the flow with the Taylor bubble being seen from a diametrical cut, transversal cut, with both cuts and the whole volume. With this, it is possible to see the bubble position inside the flow and the water layer around the air with dispersed oil bubbles, showing that the implemented routine can represent the volume in the pipe as a whole and even show specific bubble or flow parts.

However, because it does not have a routine of interpolation and smoothing of edges and outlines, the flow is represented by a composition of colored cubes. This affects the representation of the contour and body of the bubbles, differing even more from its actual shape. In addition, the opaque color assignment for fluids covering the bubble, such as water and oil, causes the reconstruction of the entire volume to prevent the visualization of the air bubble inside, being possible to see it only with longitudinal or transversal cuts in the generated image.

Even so, the advantage of flow reconstruction made with the wire-mesh sensor in comparison with the high-speed camera flow visualization is the possibility of seeing the phase distributions in the entire pipeline. In other words, with the WMS data and reconstruction algorithm it is possible to see the portion occupied by the phases at any internal flow point, while the filming with the camera method only shows the amount of light passing through the fluid along the transparent pipe without differentiating the substances inside it.

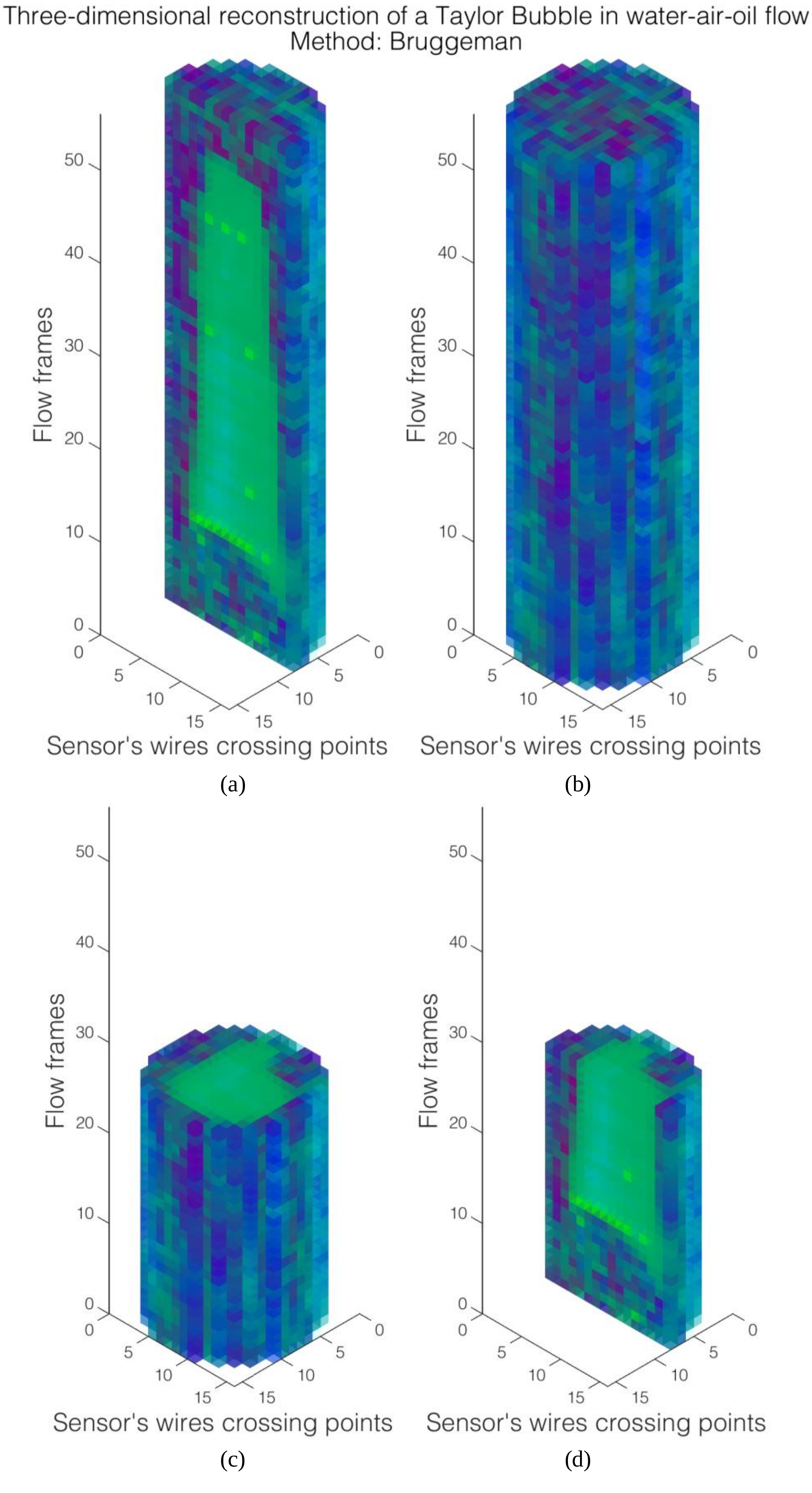

Figure 8. Three-dimensional reconstruction of a Taylor bubble in water-air-oil flow using the Bruggeman relationship model, in (a) there is a diametrical cut that shows the Taylor bubble whole length, in (b) there is the complete volume, in (c) a transversal cut in the bubble and (d) shows the bubble with a diametrical and transversal cut.

4. CONCLUSIONS

The treatment of data collected by the wire-mesh sensor is a possibility for qualitative three-dimensional reconstruction of three-phase flows. It's a low cost method for flow reconstruction and categorization that does not require a transparent pipeline like the high-speed camera method. This feature is advantageous to study fluids flowing in pipelines that cannot be made of transparent or translucent materials, or that are not in an environment suitable for routine observation, such as underwater pipelines used at oil extraction platforms. Thus, with an analysis of the parameters obtained in the section where the sensor is located, it is possible to extract important flow characteristics for optimization, control and safety of process, such as the flow pattern and phase fraction, without equipment outside the pipeline.

However, due to the necessary simplifications for the algorithm implementation and the resulting data suppression in the code routine for volume generation, there is a loss of details, impairing the meticulous evaluation of the results. Moreover, these data alone are not enough for quantitative reconstruction and therefore require other methods such as high-speed cameras to obtain flow velocity in order to reconstruct the bubble indicating its original size.

For future works, it's suggested to correct the problem of data suppression and to implement bubble identification techniques and interpolation methods to portray bubbles with smoothed surfaces and a more realistic shape, without the colored cubes aspect that have no details in the curvature contours. It is also desirable to improve color assignment method in order to provide a level of translucency to water and oil, so it could be possible to observe the air bubble even when the whole volume is being displayed.

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6. RESPONSIBILITY NOTICE