Multichannel Capacitive Imaging of Gas Vortex in Swirling Two-Phase Flows Using Parametric Reconstruction

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ABSTRACT Swirl-based inline phase separation is a promising approach in the process industry with potential application in oil and gas separation in petroleum industry. To increase the efficiency of the separation, the process may be controlled. In this direction, the position and the diameter of the gas vortex are two parameters that can be used in the control loop, provided that they can be non-intrusively estimated. This article presents a capacitive sensor-based imaging method to extract these geometrical parameters. The proposed method consists in obtaining high-temporal resolution capacitance measurements at the pipe boundary of a test rig, which in turn are used in a reconstruction and extracting the targeted parameters of the gas vortex. The calculated parameters are then used to visually present the swirling flow. The measurement system was evaluated quantitatively by performing experiments with different phantoms of known diameters and positions in the sensing area. Dynamic measurements were also performed in a test rig for liquid-gas swirling flow. The capacitive imaging system is capable of detecting characteristics of the flow for a wide range of gas and liquid flow rates. A qualitative analysis was also carried out by comparing time series of the capacitive images with high-speed camera recording. The geometrical parameters obtained by the proposed approach presents a good agreement with the real data, with a root mean square deviation of 0.76mm for diameter and 0.88mm for vortex position. It can be utilized in future work as an alternative or complementary input for the controlled inline liquid-gas separation system.

INDEX TERMS Swirling two-phase flows, capacitive sensor, grid search, parameter extraction.

I. INTRODUCTION

Many processes in the process industry there is the occurrence of multiphase flows. Various type of media are transported in different forms, and thus there is a constant need to monitor different parameters such as phase distribution and/or velocities as well as mixing or separation parameters [1]. In the oil and gas industry, the separation of crude oil from gas, solids and water is a crucial process in the production chain and plays a vital role in the quality of the extracted products. The most common techniques used for separation are based on gravity, densities and centrifugal forces [2].

One of the main disadvantages of using the gravity-based separators is the large size of the devices when the separation of small droplets is needed [3]. During the last few decades cyclonic separators got popularity for the gas-liquid separation to overcome the size problem caused in the gravitational separators. The idea of cyclonic separators can be traced back to a patent in 1940s [4]. This type of separator is able to generate accelerations much higher than the gravity (up to 100g) by swirling the two phases, thus making them suitable for offshore and subsea oil explorations [5]. In the present research, an inline type of cyclonic separator is investigated. In traditional cyclonic separators, the direction of the mixture flowing is tangentially [6], [7] while in inline separators the fluid enters axially. The inline swirl element used here
was adapted from the work of Star [8], Van Campen [9] and Slot [10] as shown in Fig. 1. The working principle for inline separators is based upon the centrifugal force. The mixture of different densities is passed through a fixed swirl element inside a pipe, and due to higher centrifugal forces, the more dense medium is pushed against the wall of the pipe creating a vortex structure having less denser fluid in the middle, which is later extracted by the pick-up tube [11].

**FIGURE 1.** Swirl element adapted from [8]–[10].

The gas vortex (gas core) created by the swirl element varies in position and diameter. To improve the separation efficiency, the size and the position of the gas core should be estimated in such a manner that it does not disturb the flow. This extracted information about the gas core can be used as a control input for valve operations. Some of the previous studies suggested the use of electrical capacitance tomography (ECT) and electrical resistance tomography (ERT) as non-intrusive methods for visualization of swirling multiphase flows [12]–[14]. However, the limitation of low data acquisition rates exists due to the measurement protocol followed by both modalities which require that all electrodes have to be activated as sender and receiver and also due to the hardware limitations. In this sense, the presented literature still lacks the geometrical parameter extraction of the gas core in the separation process concerning non-intrusive and high temporal resolution techniques.

The main objective of this research is presenting a novel approach for imaging the gas core and extracting its geometrical parameters (radius and lateral position) using high temporal resolution multichannel capacitive measurements and parametric image reconstruction.

**II. METHODOLOGY**

**A. TWIN-PLANE CAPACITIVE SENSOR**

The sensor used for this research was first proposed in [15] as a twin-plane capacitive sensor (TPS) as shown in Fig. 2a. The sensor consists of eight receiver electrodes and two transmitter electrodes for capacitance measurements. Each set of transmitter-receivers acts as an individual sensor. The receiver electrodes were placed equidistantly inside an acrylic pipe of 25.4 mm internal diameter. Electrodes were fabricated as a flexible PCB using a thin copper sheet laid over Kapton tape. A ring of guard electrodes was used to avoid any external disturbances and to confine the electric field in the region of observation. A layer of copper was also added on the outer boundary of the sensor to avoid interferences. Holes are drilled in the pipe in order to connect electrodes to the electronics using coaxial cables. The sensor electronics uses the one developed for the Wire-mesh sensor (WMS) [16], and its schematic is shown in Fig. 2b. The electronic circuit uses the time multiplexing protocol of measurements, i.e. the transmitter electrodes are sequentially activated and data are acquired from the receiver electrodes in parallel. AC voltage is applied to the transmitter electrode at the frequency of 5MHz and AC displacement current is measured at the receiver electrodes. The receiver electrodes are connected to inbuilt operational-amplifiers (op-amp), which convert the current to DC voltage values. These voltage values are digitized by a data acquisition board (DAQ) and processed using a computer. The measurement electronics is capable of acquiring data at a rate up to 1000 fps.

The main advantage of using this sensor is the ability to divide the region of interest into further sub-regions for fast measurement of phase distribution. The gas void fraction in the sub-regions is calculated as described in [17]:

\[
\alpha(i,j,k) = 1 - \frac{\varepsilon^m_{r}(i,j,k) - \varepsilon^e_{r}(i,j)}{\varepsilon^H_{r}(i,j) - \varepsilon^e_{r}(i,j)}
\]

where \(\varepsilon^m_{r}\) represents the measured relative electrical permittivity of the mixture \(m\) (water and gas), \(\varepsilon^e_{r}\) represents the relative electrical permittivity of low permittivity media (gas) and \(\varepsilon^H_{r}\) represents the relative electrical permittivity of the high permittivity media (water). \(i,j,k\) represent the number of transmitter electrodes (1-2), the number of receiver electrodes (1-8) and the frame number, respectively.

**B. PARAMETRIC VORTEX RECONSTRUCTION**

The conventional approach to obtain the electrical permittivity distribution in electrical tomography is solving the inverse problem by processing the measured capacitance aiming to obtain a reconstructed image of the investigated area. In spite the fact that the previously mentioned problem is non-linear, it is commonly approximated as a linearized model as follows [18]

\[
g = Sf
\]
where \( g \) is a vector containing the measured capacitances of the eight electrodes of the TPS, \( S \) is a linear operator, i.e. the sensitivity of each electrode to each defined position inside the pipe and \( f \) is a vector of the permittivity distribution inside the pipe. For TPS, sensitivity matrix is obtained by means of electric field simulations and details can be found elsewhere [18], [19].

In previous work in electrical tomography, regularization and optimization techniques were applied for obtaining practical and stable solutions using prior information in a non-parametric fashion [20]. Still, those types of solutions suffer from low accuracy mainly due to large quantity of variables to be estimated (all pixels of an image representing the permittivity distribution at the cross-section).

Therefore, we propose a parametric image reconstruction, which has a reduced number of parameters, formulated as a Maximum Likelihood (ML) estimation problem. First, the gas core is approximated as a circular shape. The permittivity frames are, thus, given by

\[
f(x_c, y_c, r) = \tanh \left( \sigma \left( (x_c-x)^2 + (y_c-y)^2 - r^2 \right) \right) a + b,
\]

where \( x \) and \( y \) are a grid representing the pixels in the Cartesian coordinate system and, \( a \) and \( b \) must be solved to yield the correct values of minimum and maximum normalized electrical permittivity of the investigated flow. The \( \sigma \) parameter defines the transition steepness. Typically, \( a = b = 1/2 \) and \( \sigma = 8 \). The hyperbolic tangent function is employed to generate smooth transitions and avoid abrupt changes in the modelled permittivity then, we assume that the observed signals can be modelled by

\[
g = Sf + w
\]

where \( g \) represents the measured signals and \( w \) represents white Gaussian measurement noise. Under these assumptions, the ML problem is formulated as

\[
\hat{x}_c, \hat{y}_c, \hat{r} = \arg \min \| Sf(x_c, y_c, r) - g \|_2^2
\]

To solve (5), we employ a grid search (GS) scheme, which is chosen due to its simplicity, reliability and for being trivially parallelized considering 2D space [21].

The GS method consists of an exhaustive search-based algorithm for a given set of data by defining vectors of the upper and lower bound values of the targeted parameters [22]. It was used intensively in the past for parameter extractions, for example in the field of aerospace for tracking the motion of satellites [23], in medical for allocation of sample sizes of dense Single-nucleotide polymorphism (SNPs) [24] and in optics for the optimal design of the lighting system [25].

The GS sets as the ML estimates of \( x_c, y_c \) and \( r \) the triplet yielding the minimal difference between the synthetized \( f \) and \( g \) among all possible combinations of the target parameters.

The search grid is defined by choosing the maximum, and minimum values in pixels for the \( xy \) coordinate system and for the radius. The grid resolution was chosen to be half pixel of \( 12 \times 12 \) Sensitivity matrix used from [19], i.e. the resolution is given by dividing the pipe diameter by 24 yielding 1.08 mm grid resolution. This value was empirically obtained. Further increasing the resolution does not increase the accuracy but it does increase computational time.

**C. EXPERIMENTAL PROCEDURE AND DATA PROCESSING**

Initially, the data for high (measurement of the high permittivity fluid) and low (measurement of the low permittivity fluid) calibrations are recorded using the DAQ card. After the calibration measurements, the data for each experimental point is acquired for intervals of 60s at the rate of 900 Hz. Thus, the void fraction overtime is computed for all measured points as given in (1). The parametric reconstruction starts by creating a \( (x, y) \) grid for the function \( f \) given in (3). The size of the grid is defined to have a product between \( S \) and \( f \). Since the spatial sensitivity of the sensor was investigated for a grid of 12 by 12 elements, the \( (x, y) \) grid is of the same size. The search grid containing the possible values for \( x_c, y_c \) and \( r \) is defined to have the same range of the \( (x, y) \) grid with an optimal step size. In this direction, the targeted parameters are computed by (5). After the parameters \( x_c, y_c \) and \( r \) are estimated, we can obtain parameterized 2D and 2.5D (cross section in a time series) images for representing the swirling two-phase flow, which allows visual inspection and qualitative analysis of the results. The 2D images are obtained by plotting the frames of the matrix data \( f(x_c, y_c, r) \) in a colour scale graph that represents the liquid fraction \( h_l \) (\( h_l = 1 - \alpha \)) in the pipe cross-section area, as shown in Fig. 3. Since we have computed the targeted parameters, we can choose the size of the final image...
FIGURE 5. Experiments Liquid/Gas flow facility at NUEMS. The main components shown here are Swirl Element, TPS, Camera and actuators.

by choosing the size of the \((x, y)\) grid in (2). To have a visual insight of the swirling flow over time, we stacked frames of the matrix data \(f(x_c, y_c, r)\) to plot an isosurface of the flow, as represented in Fig. 4.

D. FLOW TEST FACILITY

Flow tests were carried out at the liquid-gas flow facility of UTFPR/NUEM, Brazil. The flow facility has a LabView based graphical user interface (GUI) for real-time data acquisition and supervisory control. All the sensors and actuators used in this facility are connected via a foundation field bus network. Frequency inverter (WEG-CFW500) together with a PID controller, is used to inject the liquid at a specific flow rate using the RS-485 communication protocol that controls the speed and torque of the pump. Gas was injected by operating the needle valve manually. The facility comprises of a horizontal acrylic pipe of 26 mm internal diameter and \(\sim 10\) m in length, as shown in Fig. 5. Tap water and air were used as the target media. Tap water was stored in the tank and injected using a pump. Air is injected using a compressor, thus causing a two-phase flow in the mixer outlet. The swirl element was placed at 5 m from the inlet, and the TPS was placed 0.5 m downstream the swirl element. A high-speed camera was also installed 0.15 m downstream the capacitance sensor to visualize the gas core as a reference for the results of the presented method.

For the experiments, we performed measurements for slug flow regime. A set of 25 measurement points were chosen to observe the geometrical parameters of the created gas core. Measurement points, together with the flow map, are shown in Fig. 6. Where all points falls in slug flow regime.

III. EXPERIMENTAL RESULTS

A. STATIC MEASUREMENTS

The proposed algorithm was first evaluated performing static measurements using phantoms of different diameters and positions inside the pipe. We have built cylindrical phantoms using Polyacetal (electrical relative permittivity of about 4 [26]) with diameters ranging from 6 mm to 24 mm. To mimic the gas core wiggling, one eccentric (off-center) phantom was designed. It has 6 mm diameter, and its center is shifted 7 mm from the central axis of the pipe. The experimental procedure consisted in inserting the phantoms in the cross-section area of the sensor and fill it with water.

For the eccentric one, we performed measurements with the phantom positioned at eight different equidistant positions from the central axis of the pipe. Therefore, the phantoms simulate the gas core (of different diameters and positions) created in a gas-liquid swirling flow. Obviously Polyacetal relative permittivity \((\varepsilon_r = 4)\) is not exactly the same as for air \((\varepsilon_r = 1)\), but given the large difference to water relative permittivity \((\varepsilon_r = 80)\) we assume to be a good approximation. For each different phantom, we performed measurements, and the measured data were used as input to the grid search routine.
Table 1 summarizes the results where are shown the targeted parameters $x_c$, $y_c$ and $r$, and the deviations for each different concentric phantom. Quantitative analysis was done by comparing the computed values with the known parameters of the phantoms. The highest value for the absolute deviation of calculated diameter is 1.32 mm; the root means square deviation (RMSD) is 0.76 mm with a standard deviation (STD) of 0.72 mm. The obtained values for $x_c$ and $y_c$ were close to the ideal condition, i.e. $x_c = y_c = 13$, excluding one result (22 mm of phantom diameter) that showed a deviation of about 2 mm for the estimated $y_c$, which means an RMSD of 0.88 mm. In Fig. 7a, we show a photo of one (6 mm diameter) of the designed phantoms inside the pipe cross-section area and the 2D parameterized images for 6, 12 and 16 mm diameter.

For the eccentric case, we did not have an accurate knowledge of the phantom position with reference to the position of the electrodes. In this direction, we can compare the distance from the estimated coordinates of the phantom to the known center of the sensor $c_m$. Table 2 summarizes the results. The maximum deviation for the estimation of gas core diameter is 2.67 mm, while the RMSD is 1.92 mm with an STD of 0.58 mm. For the position of the phantom, we obtained the highest deviation of 2.19 mm and an RMSD of 1.61 mm with an STD of 1.72 mm. A union of the parameterized images of the phantom located at the eight different positions is plotted in Fig. 7b, where we also show the design of the eccentric phantom.

In Fig. 7c, it is shown the color map of the parameterized images. One possible reason for the most unsatisfactory results obtained for the eccentric case is related to the spatial sensitivity of the individual electrodes (as shown in [15]).

Despite the spatial sensitivity reached the pipe center, it is too weak in the center and strong near the pipe wall. Since the phantom occupy a small area inside the semicircle of the pipe cross-section area, it is detectable mostly by the electrodes inside that semicircle and close to the phantom. Consequently, the electrodes positioned in the opposite semicircle of the pipe cross-sectional area probably do not detect the phantom, justifying the higher RMSD for off-centered phantoms. Nevertheless, considering the case of dynamic experiments, the swirl element is designed to push the higher dense fluid against the pipe wall forming a gas core in the pipe center. In this way, we can expect deviations in a similar range as in the concentric case.

### Table 1. Geometrical parameters obtained by the algorithm for the concentric case.

| Phantom diameter (mm) | Reference | 24 | 22 | 20 | 16 | 12 | 6 |
|-----------------------|-----------|----|----|----|----|----|---|
| Grid search Abs. deviation | 23.84 | 21.66 | 19.5 | 17.32 | 13 | 6.5 |
| Calculated vortex Center (mm) | $x_c$ | 13 | 13 | 13 | 13 | 13 | 13 |
|                        | $y_c$ | 13 | 15.16 | 13 | 13 | 13 | 13 |

### Table 2. Geometrical parameters obtained by the algorithm for the eccentric case.

| Position | $x_c$ (mm) | $y_c$ (mm) | $\Delta d_m$ (mm) | Dev. $\Delta d_m$ (mm) | Diameter (mm) | Abs. dev. (mm) |
|----------|------------|------------|-------------------|------------------------|---------------|---------------|
| 1        | 19.5       | 19.5       | 9.19              | 2.19                   | 6.5           | 0.5           |
| 2        | 15.17      | 21.67      | 8.94              | 1.94                   | 6.5           | 0.5           |
| 3        | 19.5       | 10.83      | 6.85              | -0.15                  | 8.67          | 2.67          |
| 4        | 10.83      | 8.67       | 4.84              | -2.16                  | 8.67          | 2.67          |
| 5        | 8.76       | 10.83      | 4.84              | -2.16                  | 8.67          | 2.67          |
| 6        | 6.5        | 15.17      | 6.85              | -0.15                  | 6.5           | 0.5           |
| 7        | 10.83      | 19.5       | 6.85              | -0.15                  | 8.67          | 2.67          |
| 8        | 21.66      | 13         | 8.66              | 1.66                   | 6.5           | 0.5           |

### B. TWO-PHASE SWIRLING FLOW MEASUREMENTS

In this section, we present and discuss the results of the proposed system applied in the characterization of two-phase swirling flows. We measured twenty-five experimental flow points, which comprise different combinations of liquid and gas superficial velocities at a steady-state condition. In all cases, the input flow pattern observed was slug flow, as it
is also predicted by flow pattern map in Fig. 6. Since the velocities of the gas and liquid phases are different for every experimental point, the characteristics of the created gas cores will be different in the same way and shall be differentiated by the proposed system. Each measurement consisted of acquiring data from the TPS for 60 seconds at a rate of 900 fps. Afterwards the targeted parameters of the gas core were calculated for all frames. To summarize the results,
In Fig. 8, we show the calculated average of the gas core diameter and position, as well as the percentage of frames \( t_d \) corresponding to the passage of a water plug (or disappearance of the gas core). As far as the visualization of the created gas cores is concerned, we also projected the time series of parameterized 2D images that represent the average of all frames for one experimental point. This gives an overall idea of the gas core size and lateral displacement during the acquisition window mentioned above.

In general, by looking at the 2D images in Fig. 8, we notice the gas core concentrated at the pipe center for most of the experimental points. Since we measured intermittent slug flows, liquid slugs are intercalated with air bubbles in the inlet of the swirling element, and consequently the created swirling flow shows intermittent behavior as well. One can also notice that the higher the ratio of \( J_G \) to \( J_L \), the higher the gas core diameter. Fig. 9a shows a time-series generated by the TPS where we can see the mentioned intermittency. In the crossing of an elongated air bubble, the void fraction smoothly increases indicating the increase of the gas core diameter at the swirl outlet, and the bubble nose at the swirl inlet. In the time that the gas core is increasing in size (diameter), it tends to move around the pipe center until it reaches a steady-state condition. In other words, the gas core keeps the diameter and position (centered at the pipe section) almost constant until the next liquid slug reaches the swirl inlet.

![Figure 9](image)

**FIGURE 9.** (a) Time-series of 2000 frames considering the operating point for \( J_G = 0.8 \) m/s and \( J_L = 1 \) m/s (b) 2.5D representation of same experimental conditions (c) High-speed image showing the breakup of the vortex when a liquid slug got into the swirl element.

In Fig. 10, captures from the high-speed camera and 2.5D isosurface plots are representing the above-mentioned characteristics of the two-phase swirling flow. The selected frames of the high-speed camera shown in Fig. 10a are sequential and the direction of the flow is from right to left. The rectangles indicate the portions of the flow which correspond the best to the flow characteristics extracted from the TPS measurements and shown in Fig. 10b, keeping in mind that a strict correlation is not possible since the measurement protocols are different (cross-section in TPS vs. longitudinal 2D image from high-speed camera) and the measurements are done at different positions along the pipeline (15 cm distance).

For the situation in which liquid slugs are crossing the swirling element, we noticed that the small amount of gas (gas fraction less than 0.02), which comes from the breakup of the upwards gas cores, dispersed into the liquid phase not forming a gas core. In Fig. 9b, we show the 2.5D isosurface, for the same frames of the time-series, where we can see the above-described situation. In Fig. 9c, the high-speed image represents the breakup of the gas core into dispersed bubbles.

For a separation system, the situation of not having gas core at the pipe center has to be avoided. Since the proposed sensor is able to detect such situation, a control parameter can be defined as an input to the control of the separator system. In this direction, we estimated the percent time of the acquisition that there is no gas phase at the Swirl outlet, see the variable \( t_d \) in Fig. 8.

After passing through the swirl outlet, it is expected that the liquid phase will be pushed to the pipe bottom by the
The proposed system was applied in an experimental test bench designed to create a gas core centred at the pipe, which presents intercalated regions of the swirl element, and we also plotted parameterized images as averages of the whole acquired frames. The diameter of the symmetrical phantoms was estimated with an RMSD of 0.76 mm, and for the position of the gas phase the RMSD was 0.88 mm. For eccentric cases the RMSD for diameter estimation was 1.92 mm, and for estimating the position of the phantom the RMSD was 1.61 mm. Since the swirl element is designed to create a gas core centred at the pipe, we can expect the less RMSD for obtaining the gas core size and position. Qualitatively, the parameterized images showed a good agreement with reality.

For the characterization of two-phase swirling flows, the proposed system was applied in an experimental test bench that is able to run air-water flows at different superficial velocities for liquid and gas. We calculated average values for gas core position and diameter, and we also plotted parameterized images as averages of the whole acquired frames. It was possible to detect the intermittency of the swirling flow, giving the operating characteristics of slug flows at the inlet of the swirl element, which presents intercalated regions of gas core and dispersed bubbles. For this situation and for, in the future, using this information as a control parameter of the separating system, we also calculated the percent time of dispersed bubbles (or gas core vanishing), and it represented a ratio less than 4%. By comparing the 2.5D images with high-speed images, we noticed characteristics of the swirling flow, such as the gas core lateral position inside the pipe, the increasing of gas core diameter and the breakage of the swirling flow back to slug flow.

In summary, the proposed system presented good results in characterizing two-phase swirling flows, and its use can aid even the design of the controller for a separating system, which will be the focus of future work.

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