IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 10, 2018, accepted December 11, 2018, date of publication December 18, 2018,
date of current version January 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2887309

Sensing Platform for Two-Phase Flow Studies

EDUARDO N. DOS SANTOS[1,2], (Member, IEEE), ALUISIO DO NASCIMENTO WRASSE[1,2], TIAGO P. VENDRUSCOLO[1,2], NATAN S. REGINALDO[1], GABRIEL TORELLI[1], RAFAEL F. ALVES[1,3], BRUNA P. NAIDEK[1,3], RIGOBERTO E. M. MORALES[1,3], AND MARCO J. DA SILVA[1,2], (Senior Member, IEEE)

[1]Multiphase Flow Research Center (NUEM), Universidade Tecnológica Federal do Paraná, Curitiba 80230-901, Brazil
[2]Department of Electrical Engineering (CPGEI), Universidade Tecnológica Federal do Paraná, Curitiba 80230-901, Brazil
[3]Department of Mechanical Engineering (PPGEM), Universidade Tecnológica Federal do Paraná, Curitiba 80230-901, Brazil

Corresponding author: Eduardo N. Dos Santos (e.n.santos@ieee.org)

This work was supported in part by Petrobras, Brazil, and in part by CNPq, Brazil.

ABSTRACT This paper describes the development and application of a sensing platform which consists of fast conductance sensors and proper data acquisition and management software which aims at the investigation of two-phase flow parameters in pipelines. A number of sensing nodes are connected through a network which allows monitoring the flow at different pipeline positions. In addition, a data management Web-based platform is presented in order to store and manage the massive volume of data generated by data acquisition. The sensor electronics has been evaluated in temporal response and the capability to measure the parameters such as void fraction time series and structure velocities. The preliminary study of horizontal two-phase flow experiment is presented showing the capability of the developed platform to monitor flow parameters along a pipe.

INDEX TERMS Liquid height measurement, sensing platform, two-phase flow, two-wire sensor.

I. INTRODUCTION

The most common class of multiphase flows are two-phase flows and it can be defined as a mixture of two different substances in motion. The phases are immiscible substances, so that between them there are one or more interfaces or discontinuities. This type of flow is commonly found in a many industrial activities, being of particular industrial interest when the flows are confined to pipelines, for instance, in oil and gas exploration [1], [2]. Common engineering practice nowadays is to use models and software to predict the behavior of installations or equipment where such flows occur. Therefore, models and predictions are only accepted for industrial use when sufficiently validated and tested experimentally. It is very common the study of such phenomena in pilot plants, operating in controlled conditions for a wide range of pressure and temperature. Thus, industry scenarios are recreated and parameters of interest can be investigated. Hence, pilot plants equipped with appropriate instrumentation allow the measurement of local flow parameters, such as phase fraction, velocity and bubble size distribution. The void fraction is a dimensionless quantity indicating the fraction of a geometric or temporal domain occupied by the gas phase, and it is probably the most significant quantity one can measure in two-phase gas-liquid flows.

In the last decades, much effort has been given by the industry and scientific community for the development of sensing technology for two-phase flow monitoring. Many techniques have been applied to investigate two-phase flows.

Each technique is sensitive to some physical property which is different for the two phases, such as the fluid density or the electrical conductivity and permittivity [3]–[5]. An indirect way to measure void fraction is through liquid height measurement and it has been reported as a good approximation of the void fraction of the cross-sectional area at certain experimental conditions and their operability [6]–[8]. The use of wire probes to measure liquid height by though electrical conductance/capacitance measurements have been applied in many works [9]–[18]. This technique was firstly introduced by Miya [19], Miya *et al.* [20], and Tatterson [21] to determine the profiles of liquid film heights, and studied in details by Brown *et al.* [22].

The main objective of this work is to develop a sensing platform consisting of a number of distributed sensors for high-speed monitoring flow evolution along a pipeline. Moreover, an acquisition instrumentation based linear Controller Area Network (CAN) topology is presented to gather the information of distributed sensors in a pilot plant. Additionally, a data management system is developed in a web-based platform

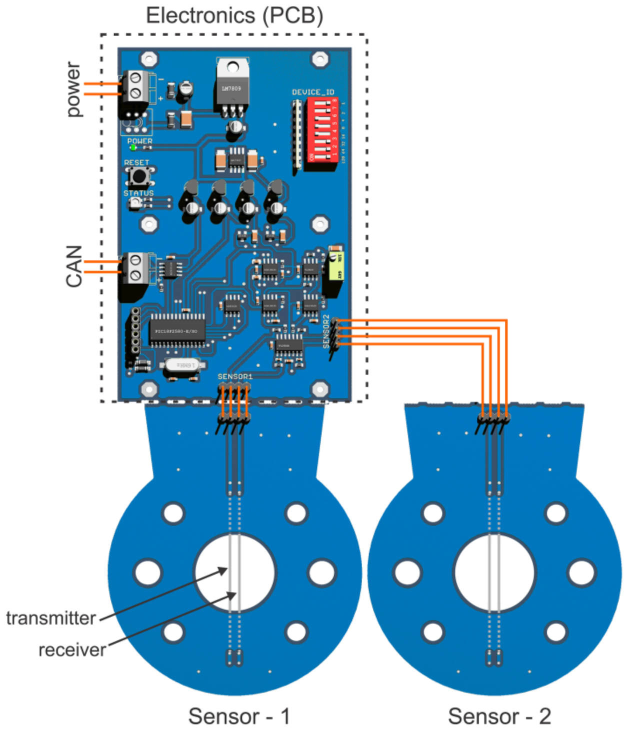


FIGURE 1. Two sensor nodes are connected to a sensing electronics.

allowing multiple connections simultaneously, providing a complete platform to store, visualize and share data.

II. TWO-WIRE SENSOR SYSTEM

The developed two-wire sensor consists of two parallel stainless-steel wires of 0.02 mm internal diameter (i.d.) placed 3 mm apart and oriented normal to the flow as shown in Fig. 1. The sensor electronics measures the conductance between the two wires. Since the gas and liquid (in this study tap water) have different electrical conductivities, the obtained conductance is a measure of the liquid content between the wires.

The sensor is built in a printed circuit board and has 1.5 mm thickness and the wires plane is oriented normal to the flow. The developed system consists of a dedicated electronics in which a PIC18F46K80 microcontroller handles the excitation signal, measurement and communications in each node. Each node comprises of two sensors forming a pair of sensors. All the sensor nodes are connected through the CAN bus in which the microcontroller built-in CAN controller in conjunction with a CAN transceiver is used to communicate with the supervisory system.

A. MEASURING ELECTRONICS

The measuring principle of the conductance between the electrodes is known as direct impedance measurement [x], in which a voltage is applied to the excitation electrode and the current flowing towards the (virtually) grounded receiver electrode is measured. This principle is also known to be immune to stray impedances caused by cables for instance. In this way, only the conductance in between the electrodes is measured.

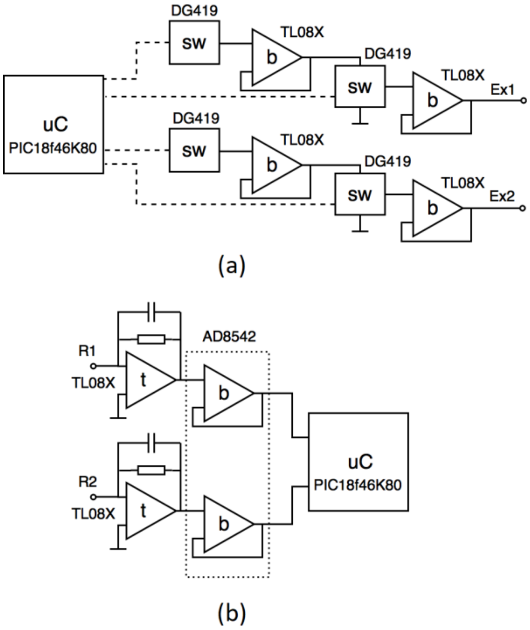


FIGURE 2. Simplified electronic circuit (a) excitation scheme (b) reception scheme.

The electronics applies an alternating voltage to the excitation electrode by means of analog switches (Maxim Integrated DG419) to create a square wave of 2.5 V and −2.5 V peaks with a frequency of 10 kHz. A bipolar excitation voltage (DC-free) is employed to avoid electrolysis effects and excitation scheme prevents the sensor to be simultaneously activated in order to prevent cross-talk. Prior the excitation, the signal is buffered through an operational amplifier (Texas Instruments TL08X), effectively providing a low output impedance (Fig. 2a). A current-to-voltage converter (TL08X based) converts the currents flowing from excitation electrode towards receiver electrode into proportional voltage and it is further conditioned with a rail-to-rail amplifier (Analog Devices AD8542) to meet the microcontroller analog-to-digital converter (ADC) requirements. The measured signal is then fed into the microcontroller 12 bit ADC with configurable acquisition rates (Fig. 2b).

B. SENSOR NODE ACQUISITION SOFTWARE

The sensor node application was developed for set-up, control and data acquisition, proving fast and easy-to-use tool for storing sensor information and performing data collection. The application communicates with the stand-alone CAN controller (CP-602E-I Series Moxa) through a PCI Express interface with capability to handle up to 255 sensor nodes. The CP-602E-I CAN interface board uses the NXP SJA1000 and transceiver PCA82C251, which provide the bus arbitration and error detection. Fig. 3 shows a diagram whereas the acquisition software communicates with the PCI CAN controller through the pool of messages. With this

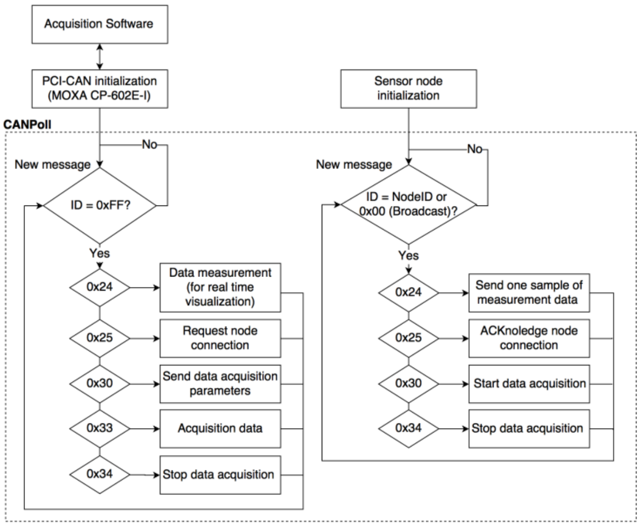


FIGURE 3. CAN protocol - Pool of messages between the acquisition software and sensor nodes.

protocol it is possible to set the acquisition parameters at each sensor node and receive the measured data. The acquired data is then exported to tabular plain text format, using coma-separated values (.csv) for an easy SQL (Structured Query Language) Databases, Microsoft Excel® and MATLAB® integration.

C. DATA MANAGEMENT WEB-BASED PLATFORM

In order to store and manage the massive volume of data generated by data acquisition, a web-based application was developed. This system consists of a client-server software that uses a website as the interface (front-end). Users can access the application from any computer connected to the internet or local network using a browser, as an alternative of using an application that has been installed on their local computer. Some of its principal advantages are cost effective development, platform-independent model, accessible anywhere, improved interoperability, security, easy installation and maintenance, and scalability. The experiment management was built using concepts like clean interface and responsive design, offering a professional user experience.

The back-end of a website consists of a HTTP (HyperText Transfer Protocol) (server, an application, and a database. Laravel (open-source PHP web framework) was chosen for back-end application development. Laravel allows to focus on the functionality in way to develop powerful web applications quickly, maintainable code, obeying several proven web development patterns and best practices. Researchers can share it using the web-interface from anywhere through a browser. This feature is important because it makes the experiment available to anyone just after uploading, avoiding data from being lost using common methods for file transfer, such as USB sticks and external hard disks. Only authorized users can access the system. After successful login, the user is redirected to timeline page, where the last ten submitted experiments are listed and can be retrieved via download.

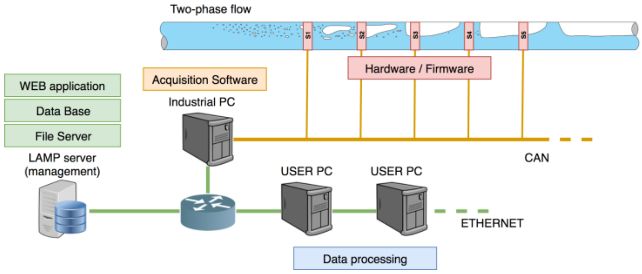


FIGURE 4. Data management web-based platform and system measurement components.

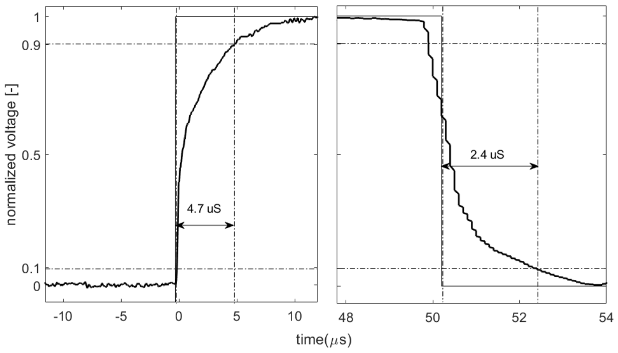


FIGURE 5. Rise and fall time of the system in which the input is the square wave.

In Fig. 4 the web-based platform is shown with the network components, in which the LAMP server is an archetypal model of web service stacks (acronym of the names: Linux operating system, the Apache HTTP Server, the MySQL relational database management system (RDBMS), and the PHP programming language. This server is connected at the internal network whereas the service is offered. The acquisition software for the two-wire sensor runs in the industrial computer and the user may upload the gathered data acquired form two-phase flow measurements. Further, users can have access through the network to the stored data being able to download it and to local processing.

III. SINGLE SENSOR RESPONSE EVALUATION

A. MEASURING TIME RESPONSE

To assess the system time response, i.e. to determine the maximum speed that a flow structure (e.g. bubble or wave) can have, still being detectable, the analog circuit step response were evaluated. The rise and fall times were obtained with the sensor flanged in a tube filled with water in which a signal generator applied a squared-signal of 10 kHz and 2.5 V_{pp} amplitude. Therefore, the signal at the output of the receiver circuit was measured with an oscilloscope in which the rise and fall times were obtained respectively for 4.7 μs and 2.4 μs, as it can be observed in Fig. 5. For one oscillation to be detected by the circuit, it must have more than twice the longest time, which is of 4.7 μs. Therefore, the measured time response (inverse of this period) corresponds to a maximal sampling frequency of up to 212 kHz.

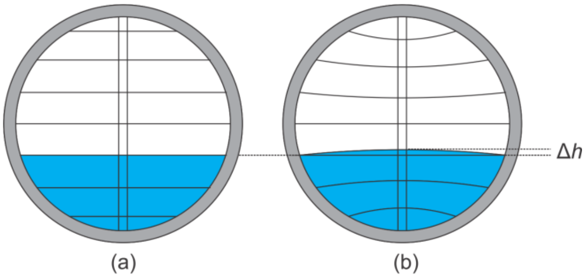


FIGURE 6. Simulated sensor geometry considering the liquid-gas interface as a (a) straight line and a (b) curved surface. **Δh** represents the difference in height.

B. FINITE ELEMENTS METHOD SIMULATION

In order to characterize the sensor electrical response, a quasi-static approximation is considered and the simulation has been made in the finite element method (FEM) commercial software COMSOL. The simulated geometry is the same of the real sensor and the emitter and receiver electrodes are set as 1 V and ground, respectively.

The electrical conductivity of the fluids was defined based on air and tap water ($\sigma = 250\ \mu$S/cm) to compare with the experimental results. Here, different liquid heights were simulated considering the interface a straight line and a curved surface. The latter is caused due to superficial tension of water in contact with hydrophobic pipe. Moreover, the curved interface creates a variable quantity in liquid height Δh, in which is unreliable to measure and is not the focus of this work. This effect is reported in [23], therefore the liquid heights and phase fraction were used to model the electric response in this work for exemplary curved interfaces as shown in Fig. 6a and Fig. 6b.

The phase fraction can be obtained by eq. 1 whereas the result will vary from zero to one when the phase height h_L is equal to the pipe diameter D. We will assume the subscript X in the following equations as L and G for liquid gas phases respectively.

$$\alpha_X = \left(\frac{A_X}{A_T}\right), \tag{1}$$

where the cross-sectional area A_X is obtained as function of phase height h_X, where $r = D/2$ and A_T is the total pipe cross-sectional area.

$$A_X(h_X) = r^2 \cos^{-1}\left(\frac{r - h_X}{r}\right) - (r - h_X)\sqrt{2rh_X - h_X^2}. \tag{2}$$

The electrical current flowing from emitter wire to receiver wire was calculated by integrating the normal flux through the receiver boundary for different liquid heights. In Fig. 7 it is possible to see the normalized output current and normalized area (i.e. phase fraction) plotted in function of the liquid height. Moreover, one can observe that two-wire probes give a linear response versus liquid height.

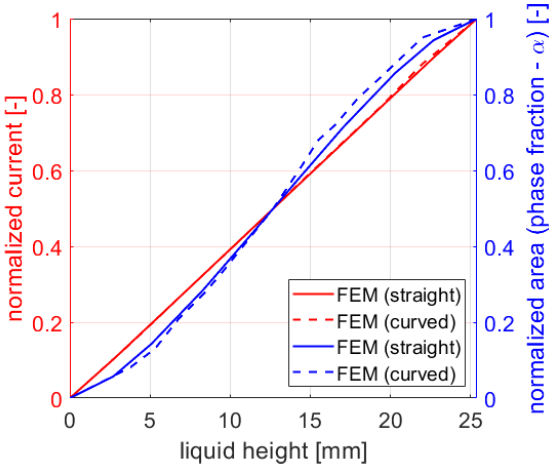


FIGURE 7. FEM simulations response varying liquid height in curved and straight interface.

C. LIQUID HEIGHT MEASUREMENT

A relationship between the spatial resolution of the sensor and its response to a stratified air–water flow was investigated. A static test was performed varying the liquid height creating a series of liquid levels. The measuring section, composed of an acrylic pipe of 30 cm of length and 26 mm of internal diameter was positioned horizontally on a scale and then filled gradually through an orifice at the top. In the experiment, 33 known amounts of water were evaluated and the liquid height was monitored. The tests were conducted with tap water (conductivity of 250 μS/cm) at a room temperature of 20 °C. For each level of water, a measurement of 5 min with a sampling rate of 1 kHz was made to ensure the accuracy of the measurements.

As observed in FEM simulations, the circuit response is linear to the liquid height in which a calibration procedure is necessary to convert the sensor readings V into a normalized value V_N. Two references measurements are required: pipe full with water V_H and empty pipe V_L as

$$V_N = \left(\frac{V - V_G}{V_L - V_G}\right). \tag{3}$$

Furthermore, gas height is obtained by multiplying the pipe diameter to the normalized sensor readings as

$$h_G = D \cdot V_N. \tag{4}$$

In this fashion, applying equation (4) in equation (2) and (1) it is possible to calculate the measured void fraction which will be further discussed.

$$\alpha_G = \left(\frac{A_G(h_G)}{A_T}\right). \tag{5}$$

Fig. 8 depicts the FEM simulations and normalized sensor measurements with linear and cubic fitting curves. Additionally, the residuals of sensor measurements from fitted models (i.e. the differences between the response data and the fit to the response data at each predictor value) is shown in Fig. 9.

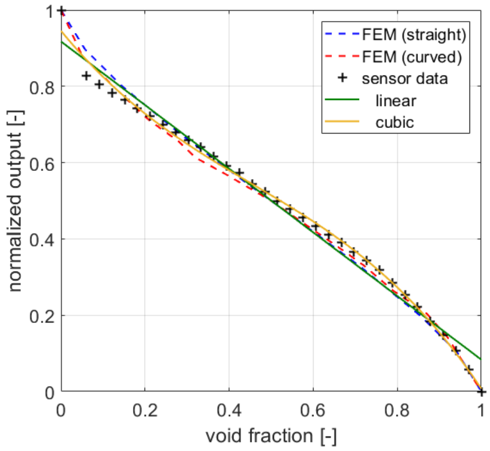


FIGURE 8. Comparison of void-fraction and sensor measurement and FEM simulations normalized outputs.

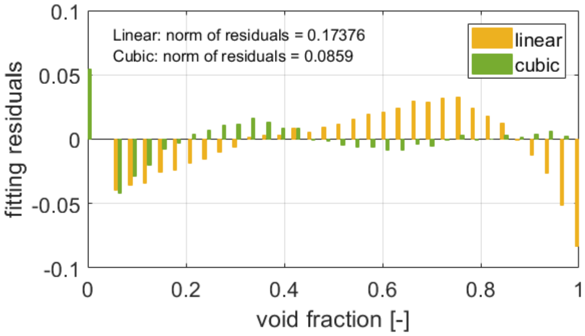


FIGURE 9. Residuals of sensor measurements from linear and cubic fitted models.

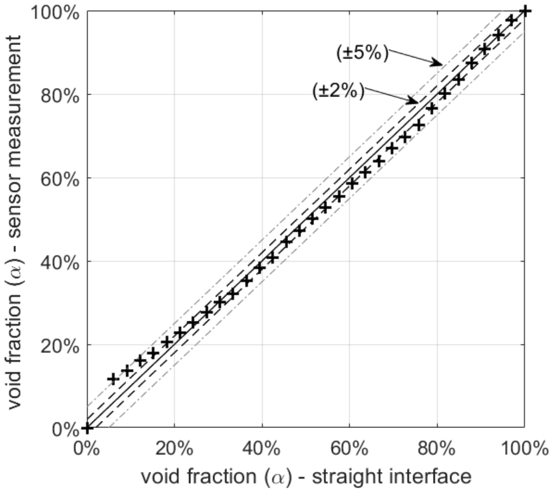


FIGURE 10. Comparison of void fraction values calculated by liquid heights with straight interfaces and void fraction values calculated from sensor measurements.

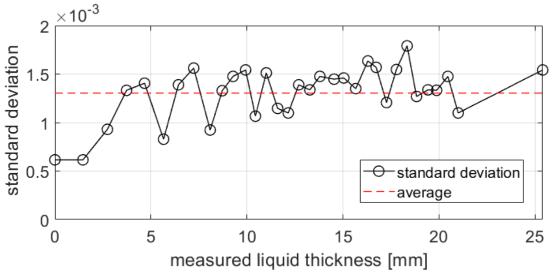


FIGURE 11. Standard deviation of each experimental condition (liquid thickness).

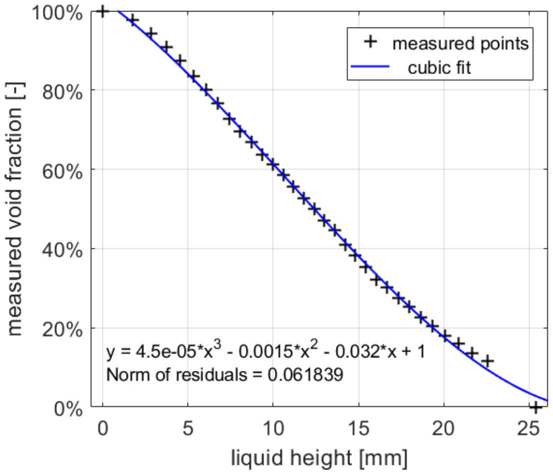


FIGURE 12. Calibration curve for theoretical liquid height input.

Void fraction values calculated by liquid heights with straight interfaces were used as reference values in comparison with the void fraction values calculated from sensor measurements (Fig. 10). It can be seen a minor non-linearity along the measurements in which for low void fraction values (i.e. high liquid height) the sensor readings tend to overestimate void fraction values. This behavior is caused by the curvature in gas–liquid interface due to surface tension as also observed in FEM simulations for curved shape vs straight interfaces.

In order to quantify the amount of variation of the measurement signal over time a standard deviation is depicted in Fig. 11. The data indicates a low deviation which is tends to be close to the mean value. Figure also shows the average of all points = 0.0013. Considering the residuals of sensor measurements from the cubic fit model, Fig. 12 presents the calibration curve for liquid height input values.

IV. APPLICATION IN TWO-PHASE FLOW MEASUREMENT

The experiments were carried out in a pilot plant at UTFPR/NUEM, Brazil. The test facility uses a virtual instrumentation supervisory control and data acquisition (SCADA) developed in LabVIEW platform, which is based on a centralized control system for gathering and analyzing real time data. The system connects the devices and allows its control through a graphical user interface for high-level supervisory management. In this work, the system deploys many sensors and actuators (e.g. valves, flow meters, frequency inverters, temperature and pressure transmitters) at different positions in the experimental facility but all connected through a Foundation Field Bus network. The liquid flow rate injected to

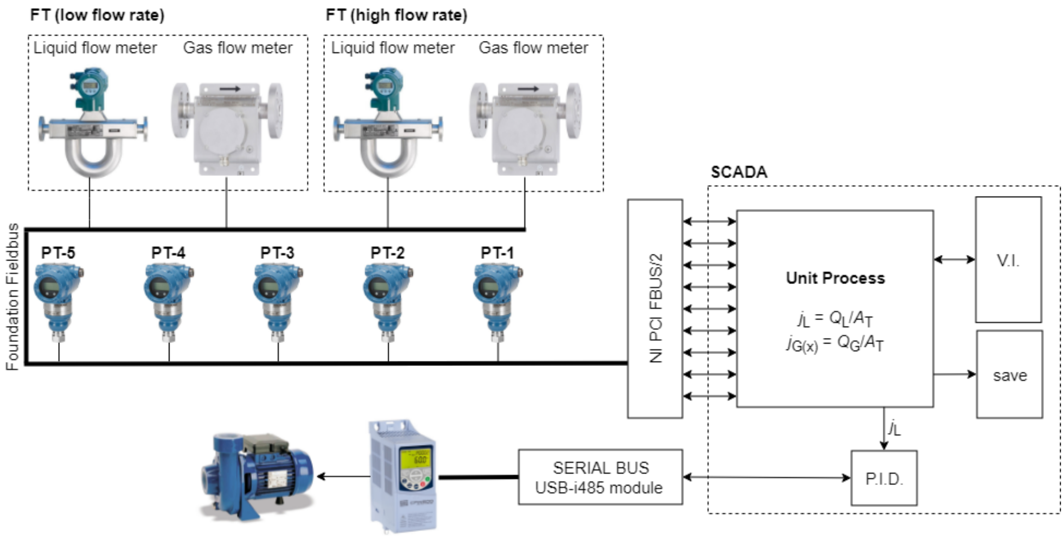


FIGURE 13. SCADA Block diagram with experimental facility components. The main components here represented are: PT-X for temperature and pressure transmitters and FT for flow meters (gas and liquid). On the SCADA Unit Process the liquid superficial velocity j_L is the ratio between the liquid flow rate Q_L and pipe cross section area A_T. Similarly the gas superficial velocity j_G is the ratio between the gas flow rate Q_G and cross section area A_T.

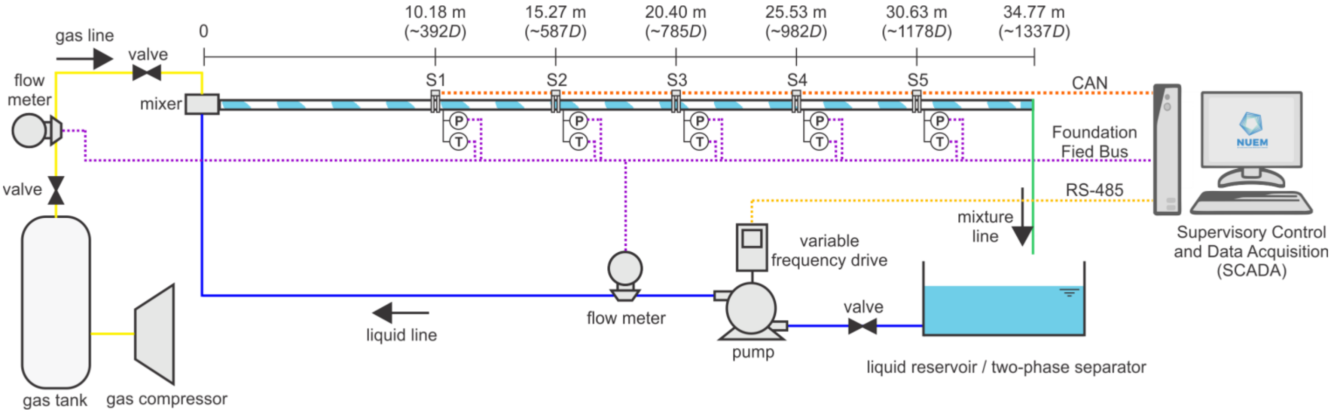
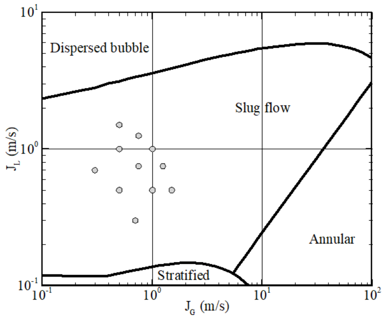


FIGURE 14. Experimental facility at NUEM and its components.



Exp. Point #	J_G (m/s)	J_L (m/s)
1	0.5	0.5
2	0.7	0.3
3	0.3	0.7
4	0.75	0.75
5	0.5	1
6	1	0.5
7	1	1
8	0.75	1.25
9	1.25	0.75
10	0.5	1.5
11	1.5	0.5

FIGURE 15. Experimental facility two-phase gas-liquid horizontal flow map.

the test facility is controlled by a frequency inverter (WEG - CFW500) with a P.I.D. (proportional–integral–derivative) controller. This communication is made through RS-485 protocol that controls the AC (alternating current) motor speed and torque by varying motor input frequency. Gas superficial velocity is controlled manually with needle valves. The information and status from the reading devices (flow, pressure and temperature meters) permits the calculation of liquid and gas flow rates at each measuring point in real time (Fig. 13).

The experimental facility comprises of a two-phase flow line of acrylic pipe of 26 mm i.d. and ~35 m long in which air and water circulate simultaneously at controlled conditions (Fig. 14). Tap water is circulated in close loop with help of a pump and a separator/storage tank. Air is injected into the pipeline through a compressor to form a two-phase flow. Flow rates of both fluids are independently measured. The two-wire node sensors are distributed along the flow line at many measurement stations #1 (10.18 m), #2 (15.27 m), #3 (20.40 m), #4 (25.53 m) and #5 (30.63 m) from the pipe entrance. Temperature and pressure, at pipe entrance and at each measurement station are monitored. Since gas is compressible, the difference of the pressures at pipe entrance and at measurement position is used to compensate the entrance

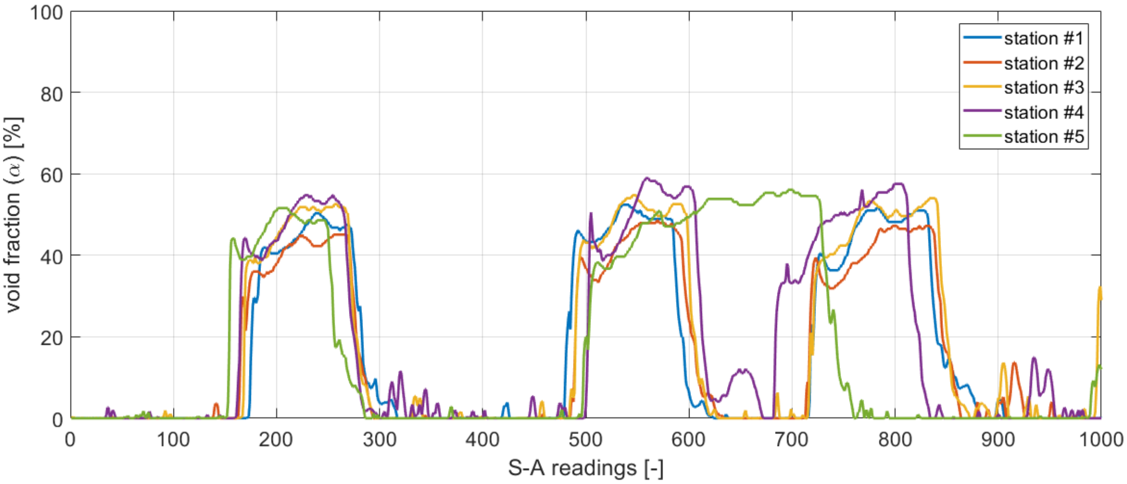


FIGURE 16. Sensor readings at different measuring stations.

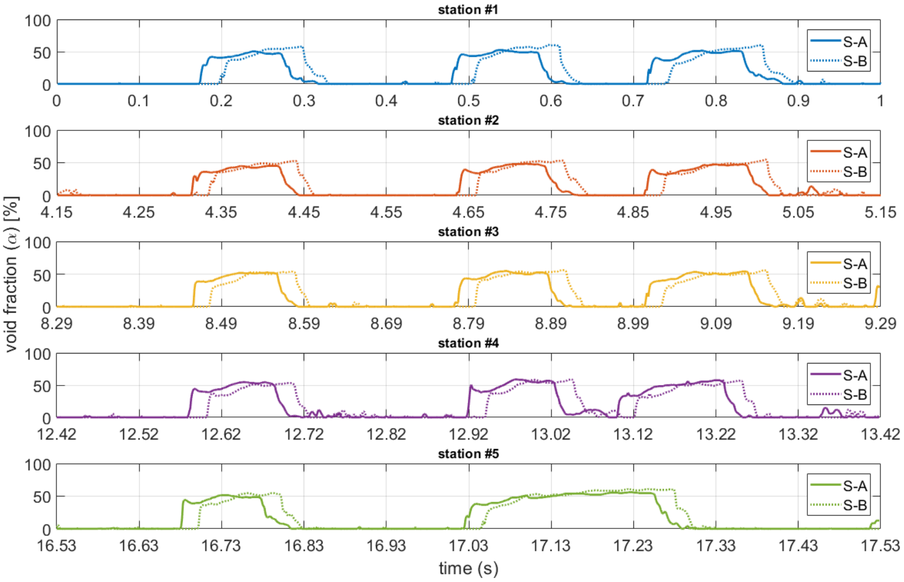


FIGURE 17. Evolution of time series along the measuring stations.

flow meter readings, assuring the exact volumetric gas flow rate measurement at the measuring test station. The typical parameter used to indicate flow rate is the superficial velocity j, which is defined as the volumetric flow rate Q (m^3/s) divided by the pipe cross section area $A_T(m^2)$.

In order to characterize the behavior of two-phase flow along the pipe both liquid and gas superficial velocity were varied forming a total of 11 measurement points as shown in the flow map in Fig. 15.

V. RESULTS

After calibration procedure, the measured data in then converted into phase fraction (i.e. void fraction) series, also known as time series at each measurement station. A number of 1000 readings (1 s) from experimental point #3 ($J_G = 0.3$, $J_L = 0.7$ m/s) was chosen to demonstrate how the flow structure (elongated bubbles) evolves along the measurement stations. Fig. 16 depicts the time series readings from sensor node A time-synchronized for each station in which it is possible to see the structures (bubble and liquid slug) increasing in velocity from station #1 to station #5. The signal acquired from station #5 shows coalesced bubble.

Observing the time series from both sensor's node (Sensor-A and Sensor-B) in Fig. 17, one can see that a pair of bubbles merging just after section #4. This behavior is mainly related to the phenomena of gas expansion and bubble coalescence. The pressure in the flow decreases towards the pipeline outlet in which the gas expands leading to an increase in the bubble length with a slight increase in its velocity. Therefore, the second bubble is reached by a higher velocity bubble summing both volume and forming new bubble, consequently longer. The liquid slug between the coalescing bubbles is

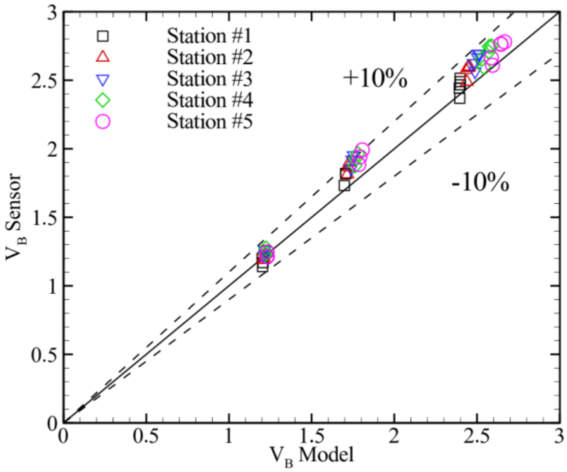


FIGURE 18. Comparison of Bendiksen's model for bubble's velocity and calculated velocity from sensor measurements.

redistributed, increasing their lengths. The increase in lengths caused by coalescence then leads to decreasing the frequency of the unit cells (bubble region and liquid slug).

The distance between the displaced sensors and the time delay of the acquired signals calculated by cross-correlation technique allows the measure of the bubble speed. In order to evaluate the overall quality of the results, a comparison of the measured values of elongated bubble velocity with the values predicted by the Bendiksen's model [24] is performed. This analysis is shown in Figure 18 for all experimental conditions in bubble velocity for each measurement station. The bubble velocity was chosen to evaluate the results because it is the parameter most susceptible to errors in the measurements, besides also influencing the values of the other parameters, such as structure lengths. It can be observed that the measured values behave as expected and that the predictions made by Bendiksen [24] are valid for our test facility too. With this, it is possible to confirm that the sensor measurements can provide valuable information for the understanding of the evolution of the flow in future systematic studies.

VI. CONCLUSION

This work presented a novel sensing platform to study two-phase flows in pipes. The assessment of sensing electronic time response and liquid height measurement has shown its capability to investigate two-phase flow at high-speed with good linearity and adequate accuracy when compared with reference values. In order to monitor the development of the dynamic flow, five sensor nodes were installed along a horizontal pipeline whereas two-phase gas-liquid flows at several conditions was investigated. Preliminary results have shown that it is possible to calculate parameters such as void fraction time series and structure velocities with good accuracy i.e. 2∼5% of the corresponding predicted values for void-fraction. Moreover, when it is used as a high-speed distributed sensor along with the data management platform, make the system a suitable tool to investigate the evolution two-phase flow in pipelines.

REFERENCES

[1] C. T. Crowe, "Gas–liquid transport in ducts," in *Multiphase Flow Handbook*, vol. 1, 1st ed. Boca Raton, FL, USA: Taylor & Francis, 2006, pp. 1–23.

[2] G. Falcone, "Heavy oil metering applications," in *Multiphase Flow Metering: Principles and Applications*, vol. 54, 1st ed. Amsterdam, The Netherlands: Elsevier, 2009, pp. 251–266.

[3] V. Bertola, "Two-phase flow measurement techniques," in *Modelling and Experimentation in Two-Phase Flow*, vol. 450, 1st ed. Vienna, Austria: Springer, 2003, pp. 281–323.

[4] W. H. Ahmed and B. I. Ismail, "Innovative techniques for two-phase flow measurements," *Recent Patents Elect. Eng.*, vol. 1, no. 1, pp. 1–13, 2008, doi: 10.2174/1874476110801010001.

[5] Y. Yong, W. Lijuan, W. Tao, W. Xue, H. Yonghui, and D. Quansheng, "Application of soft computing techniques to multiphase flow measurement: A review," *Flow Meas. Instrum.*, vol. 60, pp. 30–43, Apr. 2018, doi: 10.1016/j.flowmeasinst.2018.02.017.

[6] M. Fossa, "Design and performance of a conductance probe for measuring the liquid fraction in two-phase gas-liquid flows," *Flow Meas. Instrum.*, vol. 9, no. 2, pp. 103–109, Jun. 1998, doi: 10.1016/S0955-5986(98)00011-9.

[7] L. M. Rosas *et al.*, "Measurements of horizontal three-phase solid-liquid-gas slug flow: Influence of hydrate-like particles on hydrodynamics," *AIChE J. Transport Phenom. Fluid Mech.*, vol. 64, no. 7, pp. 2864–2880, Feb. 2018, doi: 10.1002/aic.16148.

[8] C. Wang, N. Zhao, C. Chen, and H. Sun, "A method for direct thickness measurement of wavy liquid film in gas-liquid two-phase annular flow using conductance probes," *Flow Meas. Instrum.*, vol. 62, pp. 66–75, Aug. 2018, doi: 10.1016/j.flowmeasinst.2018.05.002.

[9] J. E. Koskie, I. Mudawar, and W. G. Tiederman, "Parallel-wire probes for measurement of thick liquid films," *Int. J. Multiphase Flow*, vol. 15, no. 4, pp. 521–530, Jul./Aug. 1989, doi: 10.1016/0301-9322(89)90051-7.

[10] Z. Ruder and T. J. Hanratty, "A definition of gas–liquid plug flow in horizontal pipes," *Int. J. Multiphase Flow*, vol. 16, no. 2, pp. 233–242, Mar./Apr. 1990, doi: 10.1016/0301-9322(90)90056-O.

[11] G. Conte and B. J. Azzopardi, "Film thickness variation about a T–junction," *Int. J. Multiphase Flow*, vol. 29, no. 2, pp. 305–328, Feb. 2003, doi: 10.1016/S0301-9322(02)00130-1.

[12] G. Sakamoto, T. Doi, Y. Murakami, and K. Usui, "Profiles of liquid film thickness and drop flow rate in U-bend annular mist flow," in *Proc. 5th Int. Conf. Multiphase Flow*, Yokohama, Japan, 2004.

[13] R. J. Belt, "On the liquid film in inclined annular flow," M.S. thesis, Delft Univ. Technol., Delft, Netherlands, 2007.

[14] G. Geraci, B. J. Azzopardi, and H. R. E. Van Maanen, "Inclination effects on circumferential film flow distribution in annular gas/liquid flows," *AIChE J. Fluid Mech. Transport Phenom.*, vol. 53, no. 5, pp. 1144–1150, May 2007, doi: 10.1002/aic.11155.

[15] L. S. Zhai, N. D. Jin, Z. K. Gao, A. Zhao, and L. Zhu, "Cross-correlation velocity measurement of horizontal oil–water two-phase flow by using parallel–wire capacitance probe," *Exp. Therm. Fluid Sci.*, vol. 53, pp. 277–289, Feb. 2014, doi: 10.1016/j.expthermflusci.2013.12.021.

[16] E. dos Reis and L. Goldstein, Jr., "A non-intrusive probe for bubble profile and velocity measurement in horizontal slug flows," *Flow Meas. Instrum.*, vol. 16, no. 4, pp. 229–239, Aug. 2005, doi: 10.1016/j.flowmeasinst.2005.03.003.

[17] L. Zhai, H. Zhang, C. Yan, and N. Jin, "Measurement of oil-water interface characteristics in horizontal pipe using a conductance parallel-wire array probe," *IEEE Trans. Instrum. Meas.*, to be published. doi: 10.1109/TIM.2018.2877221.

[18] L. Xu, W. Xu, Z. Cao, Z, Liu, J. Hu, "Multiple parameters' estimation in horizontal well logging using a conductance-probe array," *Flow Meas. Instrum.*, vol. 40, pp. 192–198, Dec. 2014, doi: 10.1016/j.flowmeasinst.2014.05.021.

[19] M. Miya, "Properties of roll waves," Ph.D. dissertation, Univ. Illinois, Urbana, IL, USA, 1970.

[20] M. Miya, D. E. Woodmansee, and T. J. Hanratty, "A model for roll waves in gas-liquid flow," *Chem. Eng. Sci.*, vol. 26, no. 11, pp. 1915–1931, Nov. 1971, doi: 10.1016/0009-2509(71)86034-7.

[21] D. F. Tatterson, "Rates of atomization and drop size in annular two-phase flow," Ph.D. dissertation, Univ. Illinois, Urbana, IL, USA, 1975.

[22] R. C. Brown, P. Andreussi, and S. Zanelli, "The use of wire probes for the measurement of liquid film thickness in annular gas-liquid flows," *Can. Soc. Chem. Eng.*, vol. 56, no. 6, pp. 754–757, Dec. 1978, doi: 10.1002/cjce.5450560618.

[23] L. Nikolas, R. E. M. Morales, and M. J. da Silva, "Capacitive measuring system for two-phase flow monitoring. Part 1: Hardware design and evaluation," *Flow Meas. Instrum.*, vol. 47, pp. 90–99, Mar. 2016, doi: 10.1016/j.flowmeasinst.2015.12.009.

[24] K. H. Bendiksen, "An experimental investigation of the motion of long bubbles in inclined tubes," *Int. J. Multiphase Flow*, vol. 10, no. 4, pp. 467–483, Aug. 1984, doi: 10.1016/0301-9322(84)90057-0.

EDUARDO N. DOS SANTOS (S'13–M'17) received the bachelor's degree in computer engineering from Universidade Positivo, Curitiba, Brazil, in 2009, and the M.Sc. and D.Sc. degrees in electrical engineering with expertise in automation and systems engineering from the Federal University of Technology–Paraná, Brazil, in 2011 and 2015, respectively. He was a Research Assistant with Helmholtz-Zentrum Dresden-Rossendorf, Dresden, in 2014.

He is currently a Post-Doctoral Researcher with the Multiphase Flow Research Center (NUEM). His current research interests include sensing technology, data processing, and development of instrumentation and sensors applied to process monitoring.

ALUISIO DO NASCIMENTO WRASSE received the B.Sc. degree in electrical engineering from the Federal University of Santa Maria, Santa Maria, in 2012, and the M.Sc. degree from the Federal University of Technology–Paraná, Curitiba, Brazil, in 2015, where he is currently pursuing the Ph.D. degree with a focus on sensors and instrumentation applied in multiphase flow monitoring.

TIAGO P. VENDRUSCOLO received the bachelor's degree in electrical engineering from the Federal University of Santa Maria, Santa Maria, Brazil, in 2009, and the M.Sc. and D.Sc. degrees in electrical engineering with expertise in automation and systems engineering from the Federal University of Technology–Paraná, Curitiba, Brazil, in 2012 and 2016, respectively.

He is currently a Professor of computer engineering with the Federal University of Technology–Paraná. His current research interests include measurement technology, and instrumentation and sensors applied to multiphase flow monitoring.

NATAN S. REGINALDO joined the Multiphase Flow Research Center (NUEM), in 2016. He is currently a Junior with the Federal University of Technology–Paraná. His undergraduate research can be summarized as sensor development and system integration, related to fluid dynamics and its characterization, developing electronics and software associated with instrumentation for industrial applications.

GABRIEL TORELLI received the bachelor's degree in electrical engineering from the Pontificia Universidade Católica, Brazil, in 2013, and the M.Sc. degree in electrical engineering from the Federal University of Technology, Brazil, in 2017. He is currently an Electrical Engineer with the Multiphase Flow Research Center (NUEM). He is also an Open-Source Evangelist and a GNU/Linux System Administrator with over 10 years of experience. His research interests include asset management, cyber-physical systems, and big data infrastructure.

RAFAEL F. ALVES received the bachelor's degree in mechanical engineering and the M.Sc. degree in mechanical engineering with expertise in thermal science from the Federal University of Technology–Paraná, Brazil, in 2013 and 2015, respectively.

He is currently pursuing the Ph.D. degree with the Multiphase Flow Research Center (NUEM). He is also a Researcher with the Multiphase Flow Research Center (NUEM). His current research interests include experimentation and data processing for multiphase flows.

BRUNA P. NAIDEK received the bachelor's degree in mechanical engineering from the Federal University of Technology–Paraná, Brazil, in 2018.

She is currently pursuing the M.Sc. degree with the Multiphase Flow Research Center (NUEM), Federal University of Technology–Paraná. Her current research interests include numerical simulation and experimentation for multiphase flow.

RIGOBERTO E. M. MORALES received the B.S. degree in fluid mechanical engineering from the National University of San Marcos, Lima, Peru, in 1993, the M.Sc. degree in mechanical engineering from the Federal University of Uberlândia, Uberlândia, Brazil, in 1996, and the Ph.D. degree in mechanical engineering from the University of Campinas, Campinas, Brazil, in 2000.

He is currently a Professor with the Mechanical Engineering Department, Federal University of Technology–Paraná, Curitiba, Brazil. His current research interests include mathematical modeling, numerical simulation and experimentation for multiphase flows, and applied fluid mechanics.

MARCO J. DA SILVA (S'06–M'09–SM'15) received the M.Sc. degree in electrical engineering from the Dresden University of Technology, Dresden, Germany, and the Federal University of Technology–Paraná, Curitiba, Brazil, in 2003, and the Dr.-Ing. degree in electrical engineering from the Dresden University of Technology, in 2008.

He was a Research Associate with Helmholtz-Zentrum Dresden-Rossendorf, Dresden, from 2004 to 2009. In 2010, he joined the Federal University of Technology–Paraná, where he has been an Associate Professor, since 2013. His current research interests include sensing technology, sensor data processing, and instrumentation applied to process monitoring. He is a Topical Editor of the IEEE SENSORS JOURNAL. He is on the Editorial Board of *Measurement Science and Technology*.

• • •