CHARACTERISATION OF AIR-WATER SLUG FLOW USING OPTICAL FIBER BRAGG GRATING SENSORS

Virgínia Helena Varotto Baroncini, virginia@utfpr.edu.br
Eduardo N. dos Santos, nsantos.eduardo@gmail.com
Rodolfo Luiz Patyk, rodolfopatyk@yahoo.com.br
Maura Scandelari Milczewski, mauramil@bol.com.br
Cicero Martelli, cmartelli@utfpr.edu.br
Carlos E. F. Amaral, cmaral@utfpr.edu.br
Marco José da Silva, mdasilva@utfpr.edu.br
Cristiane Cozin, criscozin@yahoo.com.br
Rigoberto E. M. Morales, rmorales@utfpr.edu.br
UTFPR - Universidade Tecnológica Federal do Paraná
Av. Sete de Setembro, 3165 - Rebouças CEP 80230-901 - Curitiba - PR – Brasil.

Abstract. *This paper describes a new technique based on optical fiber Bragg gratings to characterize the two-phase flow of air and water. The load applied by the fluid flow on the fiber gratings is the underlying mechanism of the sensor. Experiments were carried out in flow test bed, where various operating conditions were generated and analyzed. Good agreement were observed between the results of the optical fiber sensors, the literature available mechanical models and the wire-mesh sensor.*

Keywords: *optical fiber sensor, optical fiber Bragg grating, wire- mesh, slug flow, two-phase flow*

1. INTRODUCTION

Gas-liquid two-phase flows occur in many industrial applications, such as chemical, oil and nuclear industries. Therefore, it has received much effort by the scientific community and industry for the development of monitoring solutions for such conditions since they are very common and have a large economical impact, as they may damage equipment and decrease production efficiency. This was our motive to start the development a new technique to extract parameters of interest in multiphase flows. Our goal is to achieve characterization of the gas-liquid slug flow in horizontal pipes based on Fiber Bragg Grating (FBG) method, and to compare the preliminary results of this new method, using a wire-mesh sensor.

In two-phase flow, the phases may occur in different spatial configurations known as flow patterns. The definition of the flow pattern depends on several properties, including: gas flow rates and liquid properties of the fluid (mass, viscosity and surface tension), the operating conditions (pressure, temperature, gravity, etc) and the geometric characteristics of the pipe (shape, diameter and inclination). The most common patterns in horizontal flow are known as dispersed bubble, slug flow, stratified flow and annular flow (Azzopardi 2006). Among these, the slug flow occurs in a wide range of flow rates of liquid and gas. Thus the correct monitoring of this flow pattern is of importance for various industry activities. However, two main issues limit the understanding of real world large scale problems. First, the difficulty of scaling down the problems into small laboratory models, and second, the computational demand for solving fundamental equations; although some workers have produced successful solutions to engineering multiphase flow problems, but the ultimate accuracy and the general applicability of simulations depend intrinsically on the empirical relationships obtained in experiments.

The slug flow is characterized by the succession of two distinct regions: the slug, which consists of a liquid column, and an elongated bubble. The slug region comprises a region with a large amount of liquid, and may contain small dispersed gas bubbles. A model to simulate the transient flow phenomena is the slug tracking. It is a one-dimensional, transient, Lagrangian model and using mass balance and momentum in the integral form. Barnea and Taitel (1993) presented one of the first studies using slug tracking and studied the effects of intermittency on the frequency distributions of the slug lengths. The same authors, Taitel and Barnea (1998), presented a model as an evolution of previous work in which the effect of compressibility of the gas was found. Ujang et al. (2006) presented a model based on the conservation of mass of each unit cell, but the authors treated both phases as incompressible. Grenier (1997) and Rodrigues (2009) used the control volume to obtain the equations of mass and momentum for each cell.

All mentioned models require experimental validation and in some cases empirical closure correlations are needed. Therefore, accurate measurement techniques are required. Some examples of measurement techniques are the conductive and capacitive probes (Ahamed and Ismail, 2008), x-ray and gamma ray tomography (Hervieu et al., 2002), ultrasound transducers (Murai et al. 2010), wire-mesh sensors (da Silva et al., 2010) and optical methods (Schleicher et al. 2008). Nevertheless, none of these techniques are universal applicable and may fail in practical applications.

In this paper an alternative technique is proposed using optical fiber Bragg grating strain sensors (FBG). The optical fiber gratings are placed transversally to the flow and are subjected to the forces originated by the flowing fluid. The FBG sensor measurements were compared to that of the wire-mesh sensor as well as the predicted results by numerical models. The wire-mesh sensor is a flow imaging device and allow the intrusive investigation of multiphase flows with reasonable spatial and temporal resolution. The sensor is a hybrid solution in between intrusive local measurement of phase fraction and tomographic cross-sectional imaging (Prasser et al. 1998). Hence the wire-mesh sensor is an ideal system to determine whether or not the proposed optical fiber sensing technique is feasible for characterizing multi-phase flows.

2. INSTRUMENTATION

2.1 Optical Fiber Bragg Gratting Sensor System

The basic idea is to couple an array of strain sensors based on fiber Bragg gratings in gas-liquid two phase flow. The force created by the fluid on the sensors results in the distortion of the fiber elongation. Optical fiber gratings are placed transversally to the flow and are subjected to the forces originated by the flowing fluid. Hence force components of a flowing fluid can be directly measured and relevant information regarding flow speed and flow pattern can be derived. As this technique is based on a property of the flowing fluid and not on a characteristic of the substances that compose the fluid such as impedance or optical absorption/scattering, it is possible that the two-phase flow might be characterized with a smaller number of sensors than necessary with the abovementioned conventional techniques.

The principle of FBG strain sensor is to measure the change of reflected signal from a grating when it is subjected to elongation. This change would influence the reflective index (n_b) and spatial pitch Λ at the core section of this sensor (Kang et al, 2002). According to the Bragg's law, the Bragg wavelength (λ_B) that is reflected from the sensor is given by

$$\lambda_B = 2n_b\Lambda \tag{1}$$

By neglecting the temperature effect of the sensor, the relationship between the reflective Bragg wavelength shift ($\Delta\lambda_B$) corresponding to the change of strain at the grating region ($\Delta\varepsilon_g$) can be expressed as

$$\Delta\lambda_B = K\Delta\varepsilon_g \tag{2}$$

where K is the theoretical gauge constant. In the static strain measurement, the constant K can be measured by conducting a traditional tensile test.

The optical fiber Bragg gratings were fabricated at UTFPR by directly exposing a standard single mode optical fiber to the 248 nm radiation of an Excimer Laser through a phase mask. Details may be obtained elsewhere (Paterno et al., 2011). The gratings wavelengths were 1537 nm, 1540 nm and 1543 nm and their strain optical coefficients were determined to be on the order of 1.2 ± 10% pm/με based on suggestion by Othonos (1999). A sensor unit is built by placing the optical fiber Bragg gratings in a 26 mm internal diameter pipe segment with 30 cm in length. The fibers were glued under the tension of a 20 g load using an epoxy resin to assure they were completely transverse to the flow and the gratings were positioned exactly the center of the tube. The three gratings were installed 5 cm apart from each other so that they can be used to measure speed as well as observe the flow variation along the tube.

The sensor unit is subsequently installed to the 8 m long arm of a fluid flow rig. The optical fiber Bragg grating wavelengths were monitored using a commercially available dynamic interrogator (I-MON E Interrogation Monitor). The interrogator has a repetition rate and contains a data acquisition software, providing easy setup with a laptop. It is well suited for high accuracy applications with many FBG sensors. As a broadband optical source we applied an amplified spontaneous emission (ASE) source.

The application of three gratings, installed 5 cm apart from each other, made it possible to determine the mean bubble translational velocity, through the cross-correlation of signals (Yang, 1997 and Reis, 2006). The signals were acquired through a data acquisition system, where the arithmetic operations for cross correlation and mean velocity calculation were executed

2.2 Data Processing

Cross-correlation techniques are well known and are becoming widely used in both industry and laboratory for pipeline flow velocity measurement. In gas/liquid two-phase flow, the presence of gas bubbles and the formation of liquid slugs can be detected non-invasively by various types of transducer, such as ultrasonic transducers, microwave or gamma ray devices, and capacitance (Yang, 1997). Several researchers have adopted this technique to measure bubble and slug translational velocities (Reis, 2005 and Cheng, 2005). Two similar sensors placed axially at defined distance from each other (d), are used to detect the flow pattern (slugs and/or bubbles). The signals from the two sensors ($x\ (t)$ and $y\ (t\text{-}\tau)$) are cross-correlated using the following equation. The cross-correlation signal is given by

$$R_{xy}(\tau) = \int x(t)y(t+\tau) \tag{3}$$

where $x(t)$ and $y(t)$ are the signals from both sensors. The time delay τ between the two signals is calculated using the maximum value of $R_{xy.}$ (Ruan D.et al., 2003). Hence distance d between the sensor is known, translational velocity U_T may be calculated

$$U_T = \frac{d}{\tau} \tag{4}$$

2.3 Wire Mesh Sensor

A capacitive wire-mesh sensor (Da Silva et al., 2007) was used as reference calibration system. The sensor is made of 8 × 8 wires and can be operated up to 500 Hz frame rate. Here it was applied to investigate the flow of water and air extracting the Taylor's bubble velocity. Wire-mesh sensors are flow imaging devices which are based on an intrusive principle. The sensor comprises of two sets of wires stretched over the cross-section of a pipe with a small axial separation between them. Each plane of parallel wires is positioned perpendicularly to each other forming a grid of electrodes. The associated electronics measures the electrical capacitance between the gaps of all crossing points. Since gaseous and liquid phases present distinct capacitance, the obtained sensor readings are an indication of the phase present at each crossing point. Wire-mesh sensor generates images of void fraction distributions over pipe cross section, however, in this study only the cross-sectionally averaged void fraction was used. For this reason, two-dimensional data is averaged over pipe cross section (details see Prasser et al., 1998). Hence, time series of the void fraction $\alpha(t)$ can be obtained. From the void fraction signal, a cross-correlation signal process was used to measure the bubble translational velocity between two wire-mesh sensors installed 10 cm apart. The total time for reading of all points is 2 ms, allowing a good temporal resolution.

3 EXPERIMENTAL SETUP

The experiments were performed in a two-phase flow loop made up of a 9 m long and 26 mm i.d. horizontal acrylic pipe as schematically shown in Figure 1. Controlled two-phase flows were generated and monitored. Water is stored in a reservoir and circulated in closed loop with the help of a pump while air is taken from a volume tank supplied by a compressor. Liquid flow rate is measured by a Coriolis meter and air flow rate by calibrated rotameters.

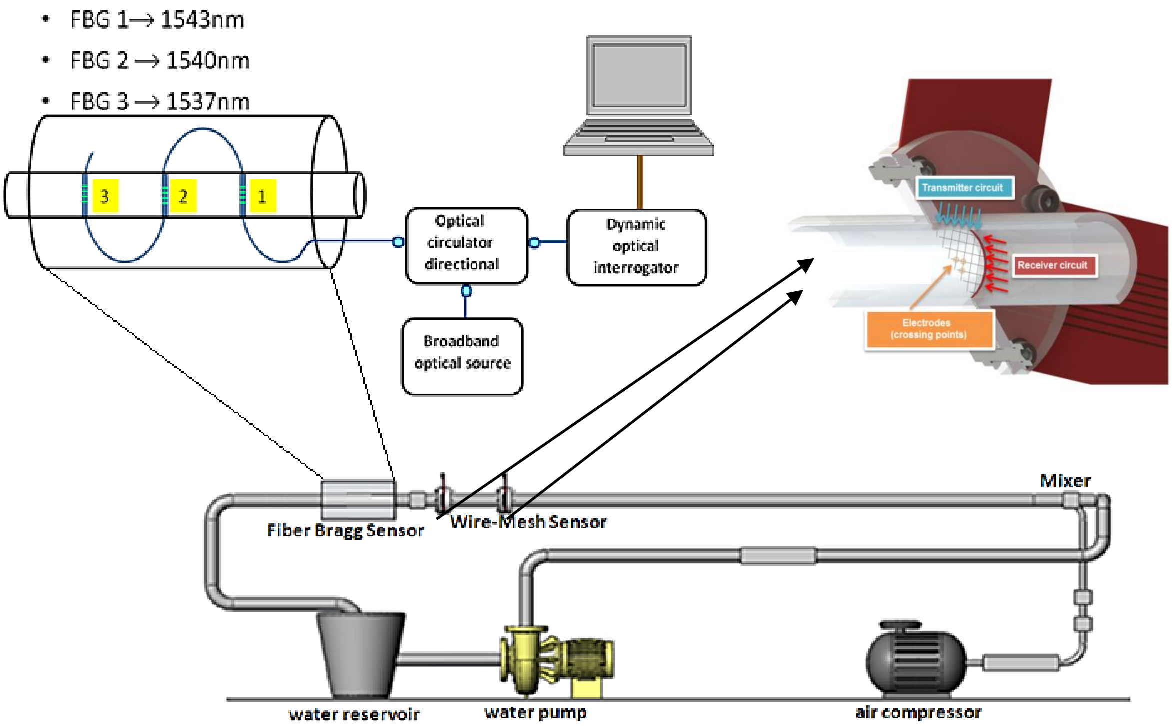

Figure 1. Experimental rig for simulating different flow regimes and the schematic drawing of the optical fiber strain sensors and the wire-mesh sensor.

The gas is mixed with the flowing water in the pipe entrance through a gas-liquid mixer, allowing a two-phase flow to develop along the pipe. In the outlet, there is a separator/reservoir, where air is expelled to the atmosphere and water reenters the system. The flow was monitored by both systems (FBG and WMS) at 8 m from the inlet, i.e. at $L/D = 308$, where L is the distance from the inlet to sensor position and D is the pipe diameter which ensures the well-developed flow under investigation. Both systems were set to acquire data at 500 Hz.

The tests were designed in the slug pattern according to the flow map of Taitel and Dukler (1976), shown in Figure 2, whereby 36 experimental points (i.e. different pairs of gas and liquid velocities) were generated and measured. The experimental results were compared with the bubble velocity calculated through the model for horizontal flow proposed by Bendiksen (1984) where bubble translational velocity may be calculated as follows.

$$U_T = (C_0 J + C_\infty \sqrt{gD}) \tag{5}$$

where g is the gravity, D is the internal diameter of the tube and J is the mixture velocity $(J=J_L+J_G)$. The flow distribution coefficient (C_0) and the tube inclination coefficient (C_∞) are parameters based on the tube characteristics and the Reynolds number.

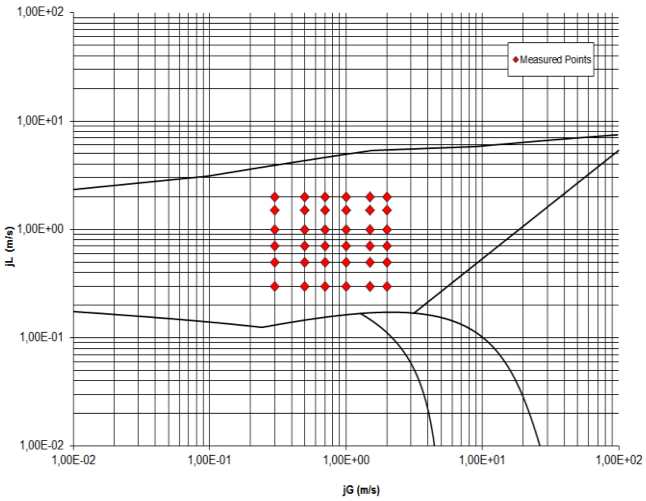

Figure 2. Two-phase flow map by (Taitel Y, and Dukler A.E., 1976) and the measured points analyzed in this work.

4. RESULTS

The raw data measured by the optical fiber Bragg grating sensors is showed in figure 3. In the presence of a slug of water the signal amplitude rises, corresponding to a maximum load being applied to the fiber. The presence of a bubble decreases the volume of water in the tube cross section (this depends on the flow regime and the superficial velocities of the water and the air) subsequently decreasing the amplitude of the forces over the fiber sensor which results on a relaxation of the strain in the fiber reaching a minimum value.

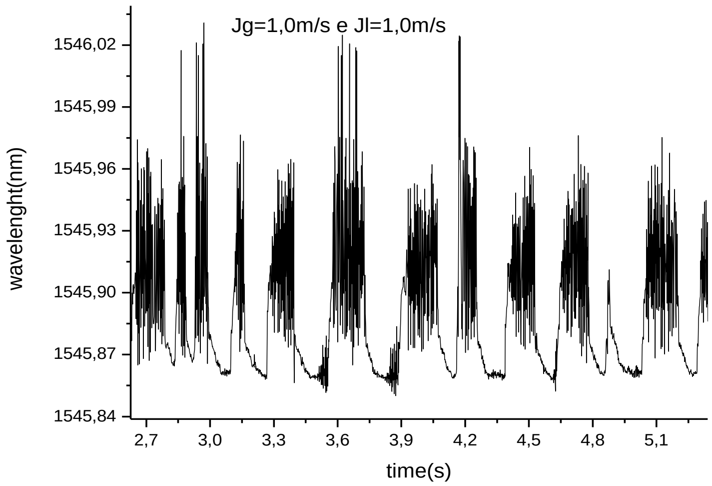

Figure 3. Response of the optical fiber Bragg grating sensor to the slug flow with J_l = 1.0m/s and J_g = 1.0 m/s.

The figure 4 show the comparison for experimental points generated and measured. The continuous line represents the values at which the bubble velocity predicted by the model and the experimental velocities are equal, the dotted lines represent values with difference of 10%. It is possible to observe that the results measured by the wire-mesh sensor and the FBG sensors are rather similar, except for high values of *J*. This could be linked to many factors including the presence of disperse bubbles in the slugs. A higher deviation of both techniques to the predicted values of the Bendiksen model is also observed which indicates that the coefficients applied (C_0 e C_∞) may need to be adapted to the current facility.

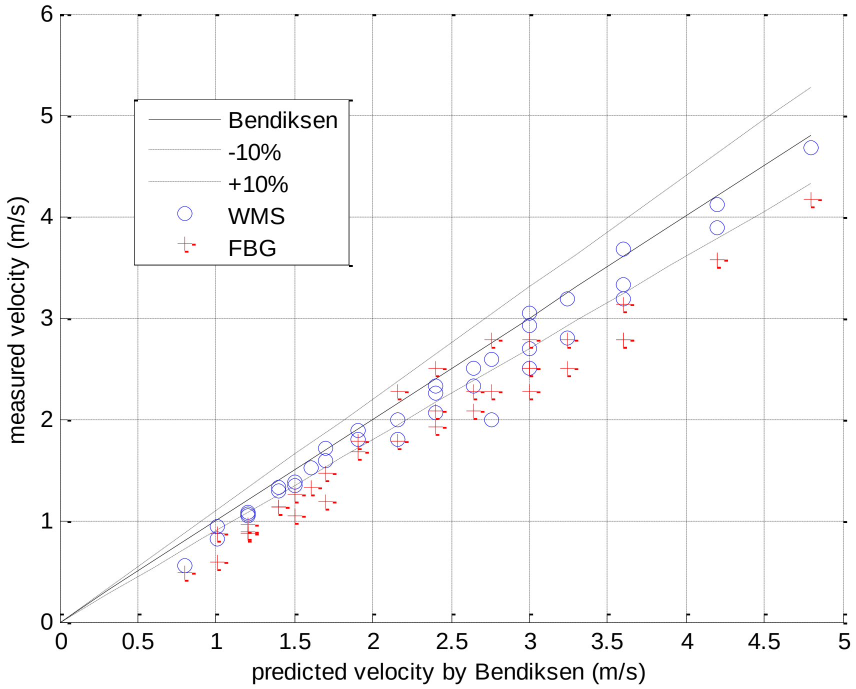

Figure 4. Comparison between the measured velocities with FBG and wire-mesh sensor as well as the predicted velocity by the model of Bendiksen.

The strain values are proportional to the force on the fiber that is also proportional to the phase fraction. Thus, to estimate the void fraction we propose a simple normalization scheme, where two references are measured: maximum load and minimum load. Hence the estimated void fraction $\hat{\alpha}$

$$\hat{\alpha} = \frac{s - s_{\min}}{s_{\max} - s_{\min}} \tag{6}$$

In figure 5 the void fraction is calculated, using the wire-mesh sensor during a slug flow, where a stream of large bubbles flow within the water, for both sensing methods. As previously mentioned the presence of a bubble decreases the volume of water in the tube cross section and decreases the amplitude of the forces over the fiber sensor which results on a relaxation of the strain in the fiber reaching a minimum value. In despite of an offset difference between the signals it is possible to observe that the overall characteristics of the flow are captured by the FBG. It is also possible to notice that the optical fiber grating sensor has a faster response than the wire mesh. The FBG sensor detects the bubbles by the variation of pressure, force and velocity of the fluid in the flow. Thus, putting the signs of the FBG sensors and wire-mesh synchronized it is clear the similarity of temporal signals, ensuring the potential of the FBG sensor characterization of two-phase flow, although further experiments are necessary to confirm the simple way to estimate the void fraction by eq. 6. The difference in units of intensity between the curves may be due the fact that the sensor wire-mesh captures data in whole cross-sectional area, while the proposed FBG sensor interrogates the flow at the central chord of the pipe.

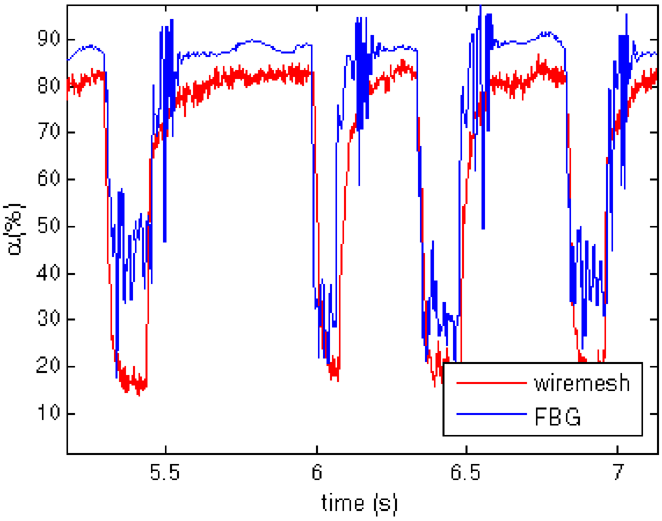

Figure 5. Void fraction measurement from wire mesh sensor and the estimation from FBG sensor. In spite of the offset difference between the signals they both follow the same trend.

5. CONCLUSION

This paper has covered a modern sensing technique for the measurement of two-phase flow. A comparative test using the fiber Bragg grating system and the wire-mesh sensor was carried out in order to validate the technique, and the very good approximation between the wire mesh and the FBG systems demonstrate the potential of the optical fiber Bragg grating sensor for flow characterization. We proved that optical fiber sensors based on optical fiber Bragg gratings are particularly suitable for applications where the characterization of the bubble or slug profiles over the piper length. The use of optical fiber Bragg grating strain sensors was demonstrated for the measurement of fluid flow in special the slug flow. The FBG measurements compared against the wire mesh present good agreement and is now being further explored to so that one can extract more parameters of flow using the flowing fluid force measurement.

A great advantage of the fiber optic against other traditional sensors is that many Bragg gratings with well separated Bragg wavelengths can be inserted within a single optical fiber allowing to multiplex up to hundreds of sensors. This means that each Bragg grating is assigned a certain wavelength range, not superimposing the wavelength of the other sensors on the same fiber. A single optical interrogation channel can therefore be used for some tens of sensors. On the other hand, when traditional sensors are adopted, each acquisition channel can be dedicated to just a single transducer. This becomes a great advantage when the number of sensors is high, in terms of system complexity and cost. FBGs have many further advantages against traditional sensors. Furthermore, light flows in the fibers instead of electrical power, thus having electromagnetic interference immunity, no possibility of short circuits, etc. The fibers are then a very thin dielectric, which can be hidden to preserve their mechanical integrity. Therefore, the proposed measurement system offers a much higher reliability and robustness, if compared to more traditional ones. The multiplexing of sensors along the pipe, as mentioned, is the principal advantage of the technique which allows the characterization of the flow and the way it changes as function of distance, curvature or geometry variations in the pipes and so on. The size and material of the optical fibers are also advantageous allowing the application of the sensor at a wide range of environments.

In a general way, the FBG sensor has shown to be suitable for studying gas-liquid flows in round tubes, allowing for extracting significant flow characteristics. It may be potentially applied not only in gas-liquid two phase flows, but also in liquid-liquid flows.

6. ACKNOWLEDGMENTS

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