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IDENTIFICATION OF TRANSIENT DIFFERENTIAL PRESSURE SIGNAL FEATURES OF TWO-PHASE FLOW IN DIFFERENT PATTERNS ACROSS AN ORIFICE PLATE

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Abstract. Phase flow rate measurement and flow pattern identification of two-phase gas-liquid flows are important to process monitoring and control in several industrial applications. The orifice plate as one of the metering devices is studied in this work to address as well the flow pattern identification of two-phase flow. Beyond the mean of the signal of differential pressure, there is the transient part that can extract a signal signature useful for one-dimensional pattern identification and flow parameters indication. To build those signatures are used PDF, PSD, and DWT as mathematical representations of the signal. The experimental procedure operates a water-air mixture that ranges from 0.03 to 0.49 m/s liquid superficial velocity j_l and 0.03 to 15 m/s gas superficial velocity j_g on a horizontal configuration of a 25.4 mm internal diameter. An orifice plate with a diameter of 12.7 mm is used as a sensing part together with a differential pressure transmitter that taps is localized 1D from both faces of the plate. The PDF of the signal showed a multimodal distribution and most of the samples present a similarity in their form and probability distribution for the plug, slug, and annular flow pattern.

Keywords: orifice plate, two-phase flow, two-phase flow metering, signal analysis

1. INTRODUCTION

Flow behavior identification of two-phase flow is important to address a good understanding of metering applicability in industry and research. In many situations, piping systems are operating a large range of gas and liquid flows which could appear in more than one flow pattern.

The present work presents a wide flow range of differential pressure characteristics across an orifice plate aiming to understand the behavior in those ranges. The mathematical representations transform the signal to a different domain whose points or means of ranges of these points could be compared among them in a relation to the superficial velocity property.

The orifice plate is a restriction that when passing mixture with low density and at some point a portion that liquid mass dominates with high density, increasing resistance, pressure variations will occur. Pressure is a rapidly transmitting energy, so the mentioned pressure variation will travel in both directions of the pipeline. This effect causes disturbances in the flow, even in that portion of the fluid that has not yet reached the orifice plate mainly because the pressure is a property that propagates to all directions in the flow which phases carry distinct compressibility as well dynamics. The structure in the flow may manifest itself in a unique pressure differential fluctuation, the orifice plate can either alter or amplify its signal. This transient signal allows us to carry out characterizations that can be used to obtain a signature of flow behavior. Those are promising and useful as inputs to data surrogated models to estimate flow pattern categorization and volumetric flux of phases.

2. LITERATURE REVIEW

The main difference between vertical and horizontal flow is the effect of gravity. In this configuration, the liquid tends to remain at the bottom of the pipe. In horizontal flow, the classification presented by Azzopardi and Hills (2003) is Bubbly Flow, Stratified Flow, Stratified Wavy, Plug, Slug Flow, and Annular Flow.

Although there are visual methodologies for pattern classification to evaluate the line operation, the determination of the pattern of a two-phase flow becomes difficult mainly due to high velocities and large diameters (Azzopardi and Hills, 2003). Pattern identification by visual observation is difficult in some cases, one of the factors is that a moving structure in a transparent tube is a piece of subjective information in two or three dimensions. Then comes the idea of passing the information of this transient behavior of the structures to a graphical representation such as the PDF of the time series of the gas fraction or differential pressure sensor signal. Graphical representation is another qualitative and objective way of classifying patterns. The author Jones and Zuber (1975) collects X-Ray gas fraction time series from a cross-section, with this time series, constructs the probability density function (PDF). These graphs, the author suggests, serve to identify patterns. Costigan and Whalley (1997) use conductance gas fraction signal to determine flow pattern with a computed PDF from this transient signal. Other authors have approached other types of sensors and statistical methodologies for signal analysis, for example, PSD, following the same line (Ma *et al.*, 2018; Santoso *et al.*, 2012). Matsui (1984) uses differential pressure signals from a vertical straight pipe section to build the PDF graph in the qualitative identification of patterns. This way of building pattern characterization is based on the static pressure between taps, and so on correlated to the quantity of liquid in this part of the pipe. In horizontal flow, the same measured magnitude was difficult in the same manner. Franca *et al.* (1991) use fractal techniques for flow pattern identification between wavy, plug, slug, and annular flow. They mention the difficult to identify patterns directly from PDF and PSD computed from a differential pressure temporal time series in a horizontal straight section with taps apart 19mm.

3. EXPERIMENTAL PROCEDURES

The temporal series of differential pressure of an experimental bench is used to relate the flow behavior to a transient signature from the signal. The experimental procedure operates ranges of 0.03 to 0.49 m/s liquid superficial velocity j_l and 0.03 to 15 m/s gas superficial velocity j_g on a horizontal configuration of a 25.4 mm internal diameter. The flow pattern of each pair taken by photograph 15D and visual observation through transparent acrylic upstream of the orifice plate was disposed on a flow pattern map. The test section used to take difference pressure fluctuations can be seen in Fig. 1 and was mounted horizontally, and comprised a plate of 3 mm with square edges orifice of 12.7 mm. It is distant 25.4 mm from the taps on each side of the plate. The development upstream section was 12.5 m long, and the mixture was discharged into a separated tank 1.6 m from the orifice plate.



Figure 1: Test section

The pattern observed is discussed how is related to the representation of PDF, PSD, and DWT as a behavior signature of the two-phase flow.

Two quantities of pressure fluctuations were used to observe the characteristics parameters from the samples of 29990 points and 30 s each. One is differential pressure signal Δp and another normalized pressure fluctuation in the times series is defined below,

$$\Delta p_Z = (\Delta p - \overline{\Delta p}) / \sqrt{(\Delta p - \overline{\Delta p})^2} \quad (1)$$

where $\overline{\Delta p}$ is the mean of pressure fluctuation. The use of the mean of samples purposes centering the distribution for the PDF representation in this text, it is more useful to use the mean of one sample when it is supposed for unknown samples of a wide range of superficial velocity.

4. MATHEMATICAL TOOLS FOR FEATURE EXTRACTION FROM PRESSURE SIGNALS

The Power Spectral Density (PSD) is drawn for each pattern and then with gas and liquid superficial velocity variation is analyzed how these parameters influence the frequency distribution. This signal analysis tool describes in the frequency domain a time series being suitable for the detection of frequency components emerging from random processes (Matsumoto and Suzuki, 1984). The Power Spectral Density function is useful for extracting characteristics in frequency. The Welch (1967) method for PSD of a discretized signal is also helpful for the elaboration of an algorithm to calculate the PSD, it is used to calculate this spectral distribution shown here. The sequential data from the sample is divided into small segments of size N-sequential points in overlapping segments. A window is applied to this segment before performing the FFT, a Hamming window was applied. Then, the periodogram for each follow-up is estimated. Finally, the power spectral density is estimated with the average of the periodograms (Xie *et al.*, 2004).

The probability for continuous variables is treated with intervals. If the probability that a real value x lies in the interval $(x, x + \delta x)$ is given by $p(x)\delta x$ for $\delta x \rightarrow 0$, then $p(x)$ is called the probability density on x . There are algorithms like the

Kernel Gaussian Estimator that builds curves closer to a Probability Density Function (PDF) based on the clustering of normal Gaussian curves (Cao *et al.*, 1994; Piryonesi and El-Diraby, 2020).

The wavelet transform is interesting for extracting signal attributes due to the ability to discriminate non-stationary signals (Daubechies, 1992). The pressure fluctuation signal depends on the flow structures which impact the staticity of the pressure signal. The transform decomposes the signal, representing it with a set of functions called wavelets. These functions of this set originate from a single function that is altered, expanded and/or contracted so that the final result represents the decomposed signal. There is a family of functions that are composed of scaling parameters, when they are given by continuous functions the transform is called continuous transform, when they are formed by integers there is the Discrete Wavelet Transform (DWT) (Subasi, 2005). The DWT could be used to analyze the signal through several deconstructions of it. The signal can be separated into several frequency bands by means of details (D) and approximation (A). Depending on how many details D are desired, the decomposition is carried out in this number of stages per filter bank, which in the end will remain these levels details and a lower frequency approximation. Briefly, the process takes place by passing the signal through a bank of digital filters. Among the wavelet family to be used for pressure fluctuation, some characteristics of the signals must be analyzed, for example, if it is a discontinuous or continuous signal, the most recommended is the Daubechies level 2 due to its smooth aspect in signals such as pressure fluctuation (Subasi, 2005; Abbagoni and Yeung, 2016). Therefore, the basic parameters of choice in a DWT are the mother wavelet used and detail level (Li *et al.*, 2016).

The Power Spectral Density is drawn with gas and liquid superficial velocity and analyzed how these parameters influence the frequency distribution. The size of the segment to calculate the periodogram was 3000 points and in Hamming window, the time series used in the study was both Δp and Δp_Z .

The fluctuation of differential pressure Δp_Z was used to compute PDF to realize a comparative study and quantify characteristics that could indicate flow parameters. The probability distribution was calculated with kernel Gaussian estimator from this distribution were took 25 equal spaced values of probability.

Features extracted from wavelet transformation include values of statical parameters as min, max and standard deviation (Übeyli and İnan Güler, 2005). Wavelet coefficients maximum and minimum are compared with the standard deviation of each point of constant liquid superficial velocity and gas superficial velocity, fluctuations in the signal have different periods and amplitudes those coefficients are more pronounced relay on the respective frequency ranges Tab. 1. It is computed 10 levels because the structures of flow have many low-frequency peaks, with coefficients showing high values in its location on each subband. The standard deviation of coefficients of the Details $std(Coeff. Wlet)$ was calculated to analyze its behavior against the flow pattern and the superficial velocities of phases. Also, the difference between maximum and minimum value $Max-Min(Coeff. Wlet)$ for Detail 9 was calculated to be understood as a feature of flow. Counting of the values of coefficient in Detail 9 bigger than its standard deviation was performed and divided by the time acquisition, named in the text f_{CWP} (frequency of high coefficient wavelet peaks) for the brief denomination. This attribute was obtained trying to capture the number of high peaks during a time in the respective subband. Intermittent flow fluctuation is expected to show some close peaks aspects regarding differential pressure transient signal. After a long period of acquisition, more events happen and a better statical parameter is achieved seeing that two-phase flow is a chaotic physical phenomenon.

Table 1: Details levels and respective frequency band decomposed 10 levels for the signal.

Detail	Frequency Range (Hz)
D10	0.45-0.97
D9	0.97-1.9
D8	1.9-3.9
D7	3.9-7.8
D6	7.8-15.6
D5	15.6-31.2
D4	31.2-62.5
D3	62.5-125
D2	125-250
D1	250-500

5. RESULTS AND DISCUSSION

The flow patterns of the flow conditions investigated in this study were well predicted by Taitel and Dukler (1976) as shown in Fig. 2. The flow visualization using the camera and visual observations through transparent acrylic was observed accordingly to the Azzopardi and Hills (2003) classification.

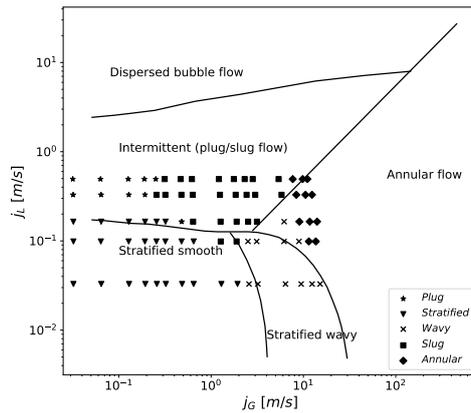
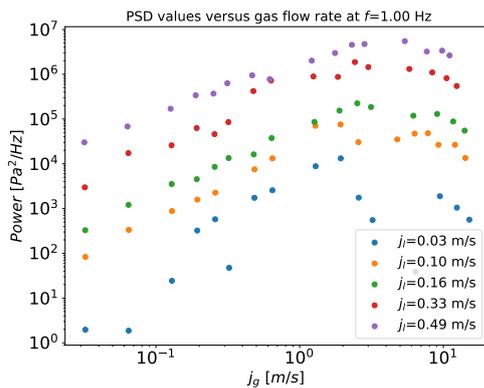


Figure 2: Flow conditions considered in this study as predicted by a Taitel and Dukler (1976) flow pattern map.

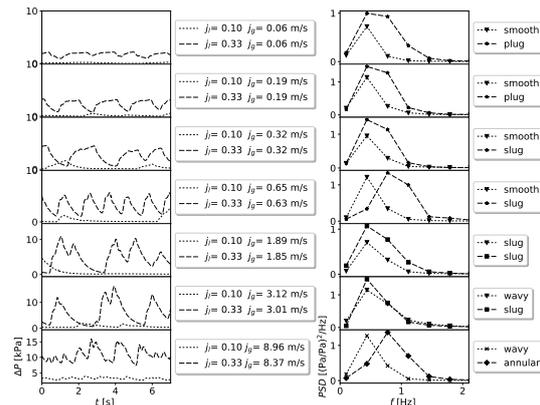
5.1 Flow characterization by power spectral density

The PSD representation of the signal shows an increase in its highest value until the transition from slug to annular flow, beyond this region there is a scattering of power density to higher frequency values compared with the peak frequency. Figure 3a shows how the value of a frequency bin evolves with the superficial velocity of the gas j_g . There is an increase of power at that frequency corresponding to pressure drop through restriction. Also, segregated flow as stratified smooth and stratified wavy do not have such tendency in $j_l=0.03$ m/s probably due to both phases passing across the orifice at the same time minimizing the fluctuation on the frequency of 1 Hz. One should note that as the length upstream is 12.5 m long some wave has an effect on the PSD for the stratified flow of a peak at low frequency, it is caused by this wave that arrives and accumulated liquid before the plate. Very low liquid superficial velocity has points without power at low frequency.

The signal of differential pressure fluctuations are seen in Fig 3b and respective PSD on the left. For $j_l=0.33$ m/s there is a scattering at low and high gas superficial velocity of the PSD to values more than 1 Hz with the exception of $j_g=0.63$ m/s middle point condition, the first situation may be caused by the passage of broken bubbles across the orifice plate and the second could indicate the high turbulence and mixture of fluids. The middle point exception shows j_g twice j_l at a slug flow pattern and change of slip direction between fluids compared to j_g less than 0.32 m/s.



(a) PSD of Δp at frequency bin of 1.00 Hz versus superficial velocity of gas.



(b) Δp signal and respective PSD of Δp_Z on the left

Figure 3: PSD representation versus superficial velocity of gas

The PSD for each flow pattern observed for the points of the experimental test was drawn together for the plug, slug and annular flow patterns in Fig 4 using the Δp_Z temporal series. The two intermittent flows plug and slug have a similar form of distribution of PSD up to 3 Hz. The major differences among the conditions drawn on each of these patterns in Fig 4a and Fig 4b are regarded as the liquid superficial velocity that shows more power at 1 Hz for $j_g=0.49$ m/s. Figure 4c shows the PSD of annular flow condition can be identified with low power at low frequency and a consistent spread to frequencies as 1 Hz and 2 Hz. It is noted that liquid superficial velocity does not change the PSD too much, demonstrating that the conditions in this pattern are more phase mixed caused by turbulence resulting in lower amplitudes fluctuations and close distribution of power in a normalized Δp_Z centered in zero.

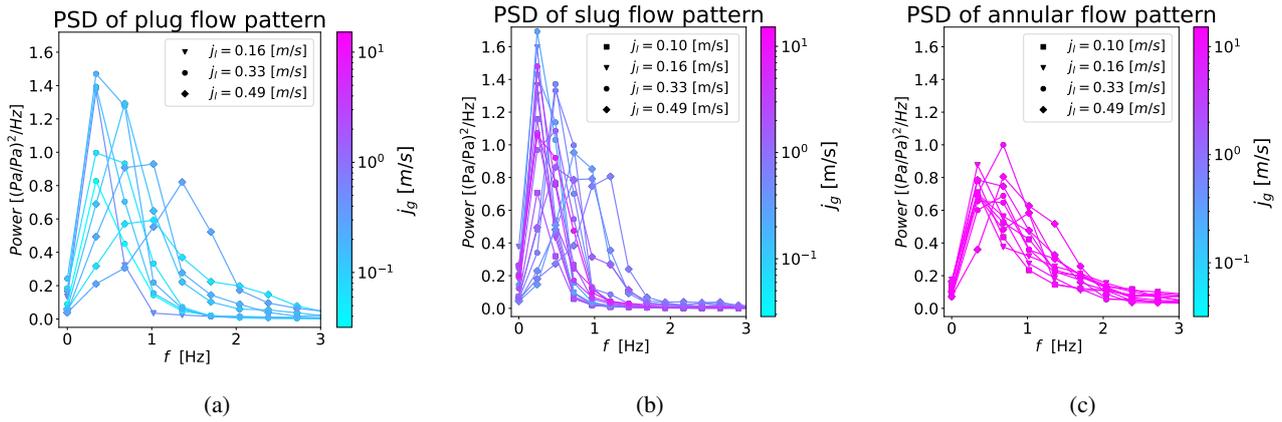


Figure 4: PSD of Δp_z temporal series

The PSD of a superficial gas velocity of $j_g=0.06$ m/s for five superficial liquid velocities is shown in Fig. 5a. It is shown more power between 1.5-2.5 Hz at $j_l=0.33$ m/s and $j_l=0.49$ m/s. The pattern observed on these points is the plug which could indicate a frequency of passage of these medium bubbles while liquid dominates. The PSD for j_g equal to 0.06, 0.65 and 6.40 were drawn and the first two cases are showing a tendency to grow power in frequencies bigger than 1 Hz, the last case with $j_g=6.40$ consequently gas superficial gas velocity much higher than liquid appears do not grow in the same way. This fact shows that the liquid carries the elongated bubbles and fluctuations caused by them are correlated in this range indicating the liquid flow parameter as well.

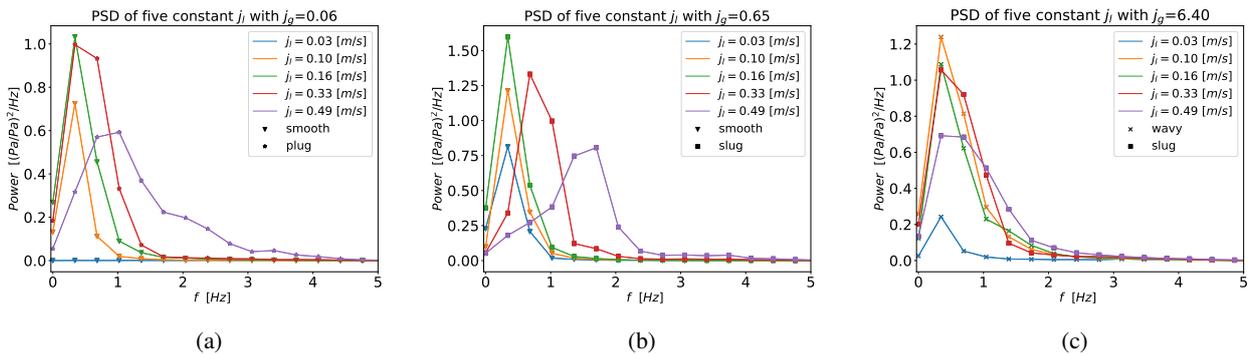


Figure 5: PSD of differential pressure temporal series

5.2 Flow characterization by probability distribution function

The PDF was used to analyze some characteristics of the flow related to pattern flow and, also, as a velocity parameter indication. Figure 6 is seen all the conditions in the range tested grouped by the respective pattern observed. The pattern indicated as plug and slug, intermittent flows, have a bimodal signature in $j_l=0.33$ m/s. The mode with a small peak on a minor value is related to $j_g=0.31$ m/s and the plug flow pattern. The mode with the tallest peak is related to a superficial gas velocity $j_g=0.63$ m/s and slug flow pattern.

Differential pressure signal from the conditions tested was normalized and drawn observing accordingly its flow patterns in Fig 6. The Plug and Annular flow patterns have a dominant probability distribution which could be used to characterize by means of these features. Some conditions of j_g and j_l escape to this dominant distribution form. The PDFs computed on conditions of lower j_l in Fig 6a have one curve distinct. Also, Fig. 6b of the Slug flow pattern show this aspect. As the PDF concentration of points is on the right-hand side, where lower differential pressure resides, long periods between peaks of pressure happen. So that can be seen as a trade-off from the probability of right side to left side when elongated bubble decreases length.

The probability distribution is analysed also as an indication of the volumetric flux of liquid or gas. Can draw the PDF of five values of liquid superficial velocity for a constant gas superficial velocity as in Fig. 7. At $\Delta p_z=1$ it is seen a correlation of liquid superficial velocity with probability on the position. These values $\Delta p_z>1$ represent the peaks of signal in which low j_l has less peak in a period and high j_l shows a flat distribution at this gas superficial velocity. This flatness is evidence of fluctuation close to a square signal form, the cause might be the intermittent passage of almost pure liquid across the orifice and then the passage of a mixture of liquid and gas in approximately equal time. On the other

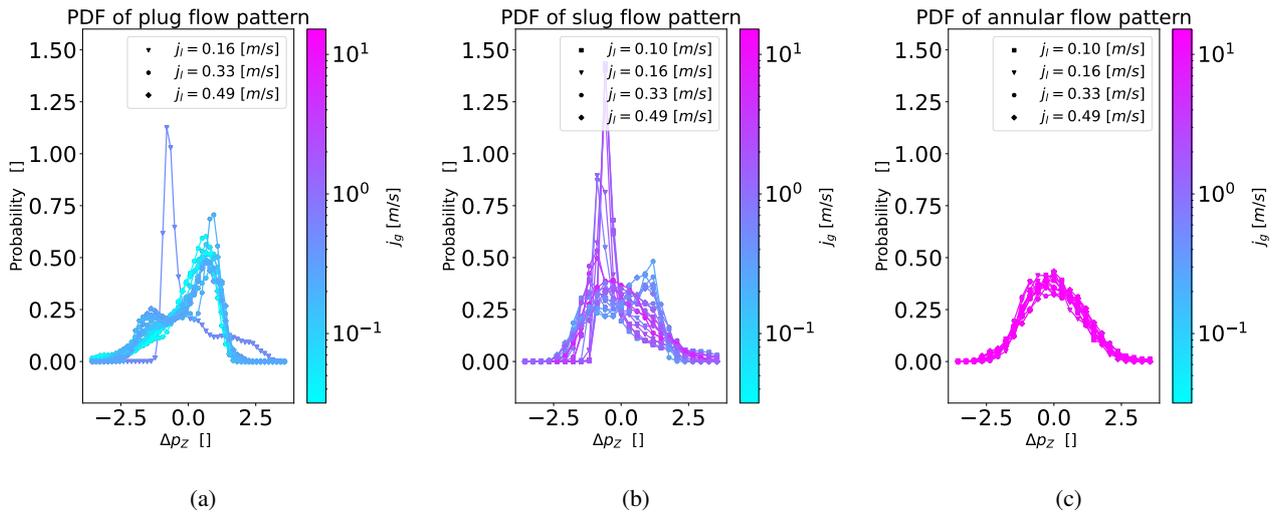


Figure 6: PDF of differential pressure temporal series grouped in flow patterns

side was an inverse relation, but need to change looking at the interval of $-1 < \Delta p_z < 0$ to see a tendency of concentration of probability of pressure at the bottom as low quantities of peaks in the signal on the sampling period. For the gas superficial velocity range of 0.13 m/s to 3.14 m/s, the same characteristic is shown. The sample period is a parameter that can change the distribution, a minimal sampling period that could unchanged this probability distribution. Figure. 8 are shown this variation in the time period of sample and respective PDF, in less than 10 seconds can be seen a change in distribution. Therefore, a long period must be used to achieve the previous conclusion. Figure 9 is evidence that a liquid flow feature indication can be explored in the PDF values throughout fixed values of j_g .

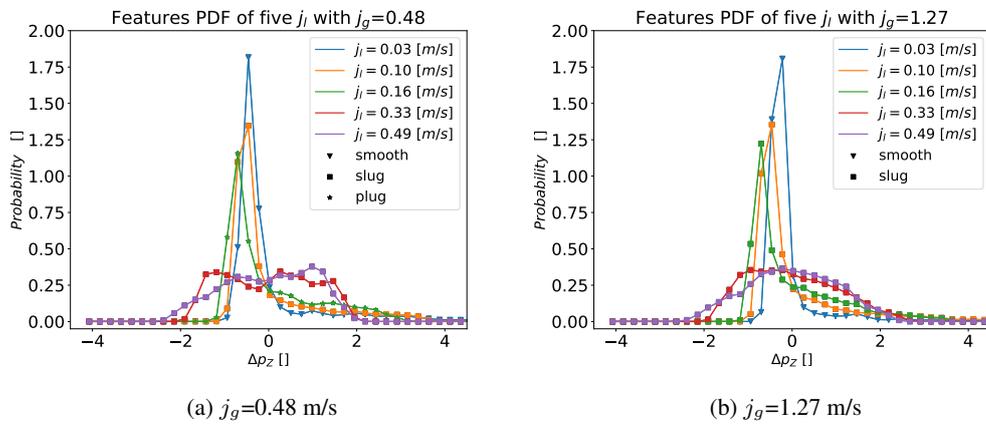


Figure 7: PDF at $j_g=0.48$ m/s and $j_g=1.27$ m/s.

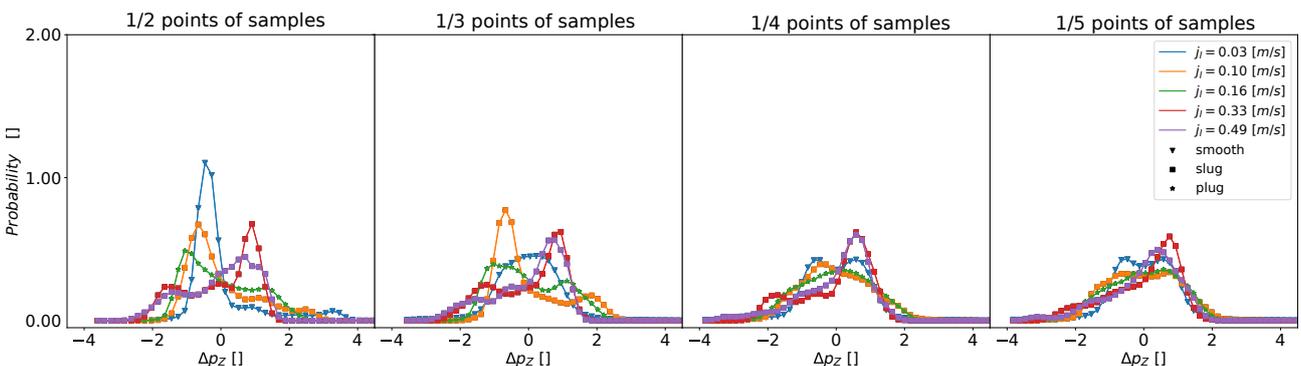
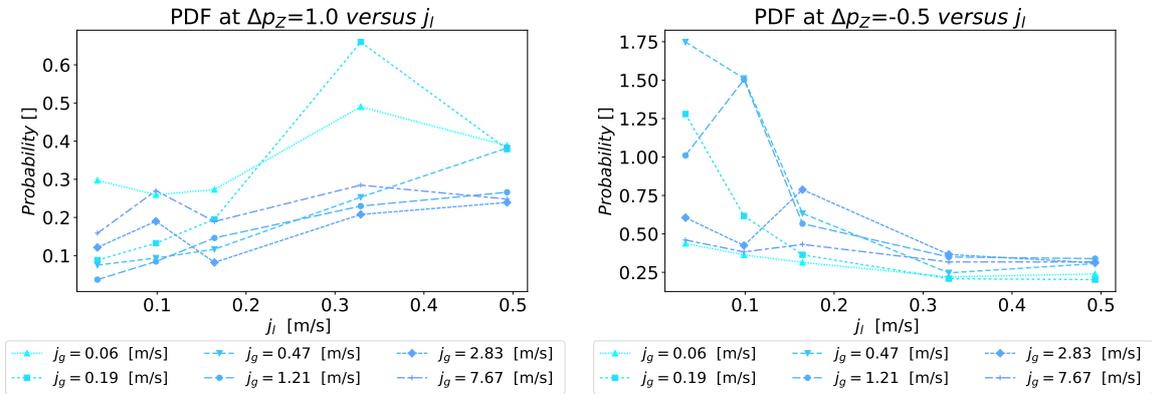


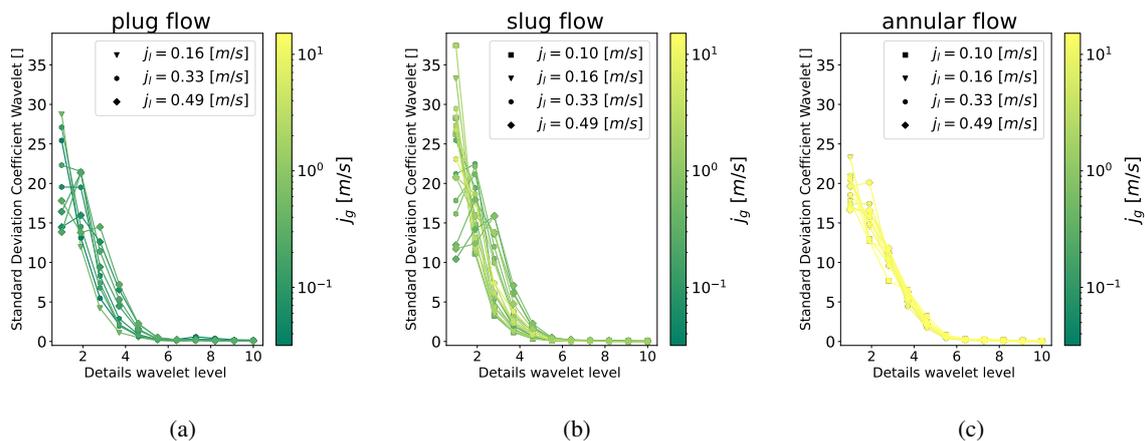
Figure 8: PSD of differential pressure temporal series using each sample divided by 2,3,4,5



(a) (b)
Figure 9: PDF at picked values of Δp_z versus j_l .

5.3 Flow characterization by discrete wavelet transform

Characteristics of flow can be analyzed in a discrete wavelet transform. Depending on the number of points of the sample, one can obtain a number of coefficients called *details*. This array of coefficients composes values of the scale or stretch of a function known as a wavelet, the position and value of these coefficients are coincident with the position and size of amplitudes in a signal. Figure 10 shows the standard deviation values for each detail, one of the parameters used by Abbagoni and Yeung (2016) to characterize the flow by means of an ultrasonic sensor. In Fig. 10 points of Details versus Standard Deviation are plots separated for the plug, slug, and annular flow pattern. There is not much similarity in each plot to the correspondent flow pattern, but it can be observed in each *details* feature as well.



(a) (b) (c)
Figure 10: Coefficient Wavelets Standard Deviation of Δp_z in Details Levels

The coefficient wavelets Standard Deviation of Δp_z of Detail and liquid and gas velocity could characterize the flow across the orifice as seen in Fig. 10. For that, a plot of Detail 10 and gas superficial velocity were drawn for five values of j_l as can be seen in Fig. 11a

Besides the Fig. 10 do not present visible correlation, Details 1 was drawn against variation of superficial velocity of phases. Figure 11 shows an approximated curve tendency with the volumetric flux of gas, it emerges as a feature to indicate flow parameters by analyzing differential pressure fluctuation.

Authors use the value of Details as features for pattern recognition, using for each detail the maximum, minimum, mean, and standard deviation (Übeyli and İnan Güler, 2005). Here it could be compared the difference between maximum and minimum and the standard deviation, as the pattern recognition uses the latent variables the determine some parameter and if the flow is the target variation on its depending. Figure 11 shows these two characteristics against liquid and gas

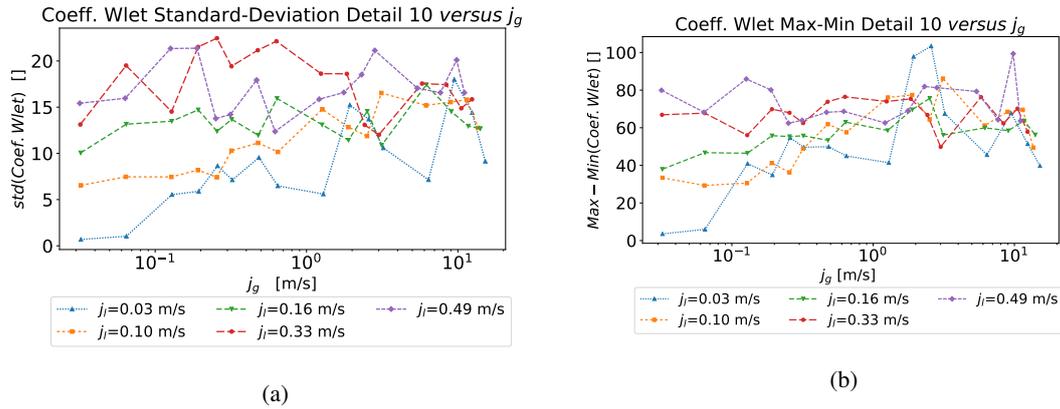


Figure 11: Detail 10 relation with superficial velocity of phases

superficial velocity. Both variates in the same form, if they are normalized, as might happen in a pattern recognition process one can use just one of them, not needing more than the standard deviation of details as a feature.

Figure 12 shows the number of coefficient wavelets in Details 9 that is bigger than the value of standard deviation, aiming to count the peaks during the transient differential pressure signal. It is an interesting feature because the coefficient wavelet emerges at a high value when the respective frequency of that peak wave is within the range of Detail analyzed, in this case, Detail 9 is 0.97-1.9 Hz range. A tendency is seen with the superficial velocity of the liquid if observe in specific ranges of intermittent but shows a high deviation from a smooth curve tendency for superficial gas velocity.

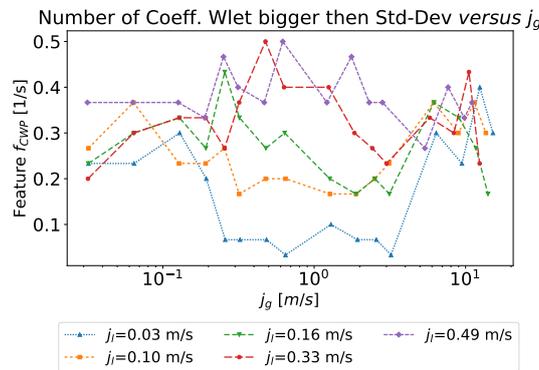


Figure 12: Detail 9 relation with superficial velocity of phases for time sample of 30s

6. CONCLUSION

The use of orifice plate to identify flow characteristics as flow patterns and parameters of superficial velocity is promising and useful to selected features. This study analyzed the relation of features comparatively to liquid and gas superficial velocity of phases in a mixture in a range of conditions. One conclusion from the mathematical tools to construct a feature used is that all of them show a correlation to the liquid phase velocity, still, there is a more chaotic tendency relation with gas superficial velocity. The period of acquisition longer may show a less chaotic tendency. Machine learning methods applied possibly will offer less precision to determine flow parameters of gas. A study with other sensing devices can be analyzed in the same way and verify less chaotic behavior in relation to the gas phase.

These characteristics shown and analyzed in this text emerge features to be used in machine learning methods like neural networks to identify flow patterns and could be used as well in the range conditions to estimate the flow of phases.

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