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EVALUATION OF TWO-PHASE FLOW PATTERNS USING CHROMATIC CONFOCAL MICROSCOPY

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Abstract. *Two-phase flows have important applications in fields such as oil and gas industries, refrigeration and power generation. In these flows, the phases have numerous dispositions, called flow patterns, according to the operative conditions, such as mass flow, temperature, flow inclination, fluids, and others. The flow pattern has a strong influence on several parameters, which motivated the creation of various flow pattern maps. While important, its determination is usually subjective, using videos or photos from high-speed cameras. In addition, there is no consensus on the nomenclature, as the same flow pattern can be classified in various ways by researchers. Objective flow pattern classification methods exist, such as statistical analysis or comparing change of inclination on a pressure drop curve, which motivates research on the topic. This paper addresses the issue, proposing a new flow pattern detection technique, using the output signal of the chromatic confocal microscopy, which is an optical instrument that provides distance measures of interfaces between transparent mediums, used mostly in health sciences, and novel in two-phase flow applications. The technique consists of calculating the probability density function of the sensor's output, and comparing it with the observed flow pattern. The probability density function of each flow is different, and thus can be used to determine transitions. To validate the technique, stratified and intermittent flow patterns were observed on a horizontal air-water flows in a 6.40× 5.0 mm*^{2} $(b \times h)$ *and a 12 mm squared channel. Results pointed that stratified and intermittent flows have a very distinct patterns, encouraging the development of the technique*

Keywords: *two-phase flow, air-water, flow pattern, chromatic confocal microscopy*

1. INTRODUCTION

Two-phase flows can be classified in different flow patterns, according to the topology of the flow. Those flow patterns are a function of the fluids, channel size and material, and operating conditions. A major classification would be in dispersed and separated flow (Thome and Cioncolini, 2016). Usual dispersed flows are bubbles and mist, while separated flows are intermittent (plug and slug), stratified and annular. Visualization of each flow pattern can be found on (Triplett *et al.*, 1999; Thome and Cioncolini, 2016). Flow patterns are usually classified using high-speed cameras. Due to the subjective nature of visual classification, new objective methods are desired to classify flow patterns. One strategy to do that, is using the change in signal obtained when measuring the liquid thickness in separated flows, which in itself is of special importance, as it can be used to calculate the void fraction, and also it is used in mechanistic models for heat transfer and pressure drop (Thome *et al.*, 2004; Cioncolini and Thome, 2013)

Tibiriçá *et al.* (2010) reviewed several techniques for liquid film assessments, and classified them in acoustic, electrical, optical and nucleonic. Techniques differ on precision, cost, applicability for various channel sizes and fluids. The authors highlight that the confocal chromatic microscopy is an interesting technique, much used in microbiology applications due to its precision, yet little explored in fluid mechanics.

This study addresses this issue, classifying flow patterns using the probability density function of the signal of the chromatic confocal sensor, when measuring the liquid thickness in separated flows. For that, stratified and plug flow patterns are evaluated in horizontal air-water flows, using a rectangular 6.40× 5.0 mm^2 $(b \times h)$ and a squared 12 × 12 mm^2 test sections.

2. METHODOLOGY

Figure 1 shows the schematic of the experimental rig used. It has a line of compressed air, and one of liquid, that mixes at the beginning of the test section, exiting the test section in liquid separator, closing the circuit. The gas flow is measured using a orifice plate, while the liquid flow is measure using a turbine flow meter. Liquid and gas flow are adjusted using needle valves.

Two test sections were used, both with 150 cm length. The first is a squared $12 \times 12\,\mathrm{mm}^2$ channel made of aluminum. A visualization section made of acrylic visor with 2.6 mm thickness was installed 90 cm from test section beginning. The second test section is a rectangular channel with $6.40\times 5.0\,\mathrm{mm}^2$ $(b \times h)$. The bottom and lateral sides are made of aluminum, while the top is made of acrylic with 6 mm thickness.

The chromatic confocal sensor, used to measure the liquid film thickness, consists of a controller and a probe, united by a fiber optic cable. The controller is isolated, while the probe is above the test section, at about 90 cm from the start of the test section.

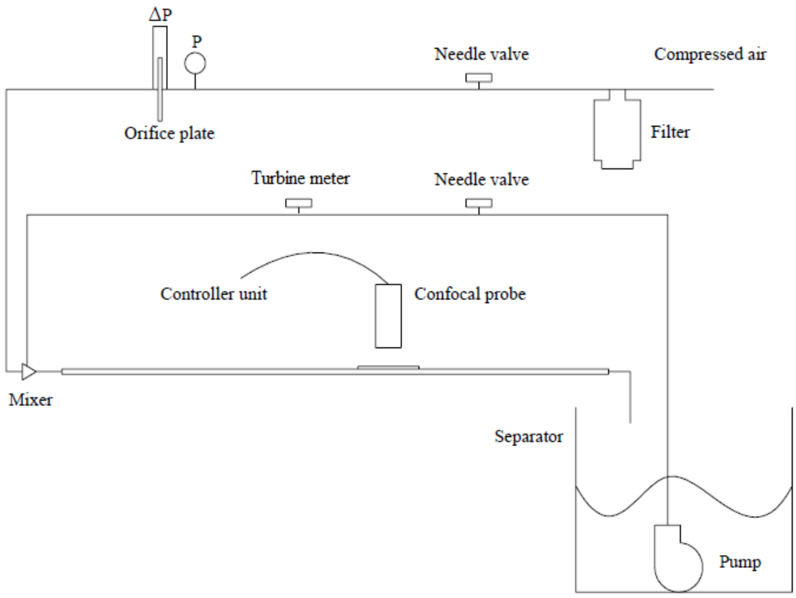

Figure 1. Experimental rig schematic

2.1 Liquid film measurement

Figure 2 shows a schematic of the chromatic confocal measurement principle. It works as a light source in the controller emits a white light, that goes to the probe via fiber optic cable. Then, the light is dispersed in the various wavelength through a set of lens, resulting in a conic shape with all wavelengths. All of them are focused on the same center point, varying only the height coordinate. When in contact with a surface, there is a focal reflection, that goes through a pinhole, and is evaluated in a spectrometer. The wavelength of the focal reflection corresponds to a distance, via factory calibration.

When used on transparent mediums, part of the part refracts. This can be used to measure several distances, as each change in medium corresponds to a focal reflection. The thickness can then be evaluated using the difference in distances. One important aspect to take care is to make a refractive index correction, as the light changes direction in each medium change. This can be done automatically through the software of the sensor.

2.2 Detecting flow patterns

The confocal chromatic microscopy is specially adequate for measuring liquid thickness in separated flows. One way to identify flow patterns is evaluating the probability density function of the temporal output of the sensor. In stratified flows, it is expected to have a peak value on the mean height, with small oscillations corresponding to waves. In intermittent flows, it is expected to find two distinct pictures, one corresponding to when there is only liquid flowing, and the other for the liquid film between the channel and the gas bubble. Annular flows, despite not being the object of this study, is similar to the stratified flow, but with a much lower liquid film thickness.

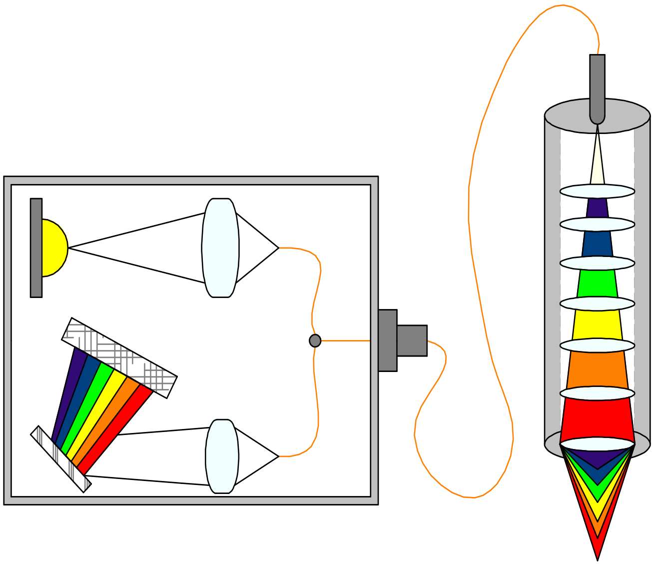

Figure 2. Confocal chromatic schematic

2.3 Signal treatment

The probe used has a measuring range of 10 mm, and an acquisition rate of roughly 670 Hz, which corresponds to one measurement each 0.0015 s. The corrections of refractive index are made directly by the control units, so no changes were needed. The sensor outputs a missing value on two distinct occasions, the first is when the interface is bellow its measuring range (happens during plug flows, when the liquid plug passes); the second is when the light hits the interface at a high angles, approximately 30° (this happens more frequently the more turbulent is the flow). While possible to make more refined treatments, we chose to substitute the missing values by the height of the tube, or simply ignore the data. Each treatment will be referenced on the next section when appropriate.

3. RESULTS

Figure 3 shows the profile of two flows obtained in the 12 mm squared channel. The plug flow has superficial velocities of $j_l = 0.25\,\mathrm{m/s}$ and $j_g = 0.10\,\mathrm{m/s}$. The thickness can be thought as the level of the liquid column. In that sense, the plug flow has liquid columns below the gas bubbles ranging from 5.40 to 6.10 mm; and considering the channel dimensions, the bubbles are about 6.2 mm high. It is important to highlight that there several discontinuities on this plot, which are indicative of the liquid plugs. In this case, a liquid plug is passing occupying the entire cross-section.

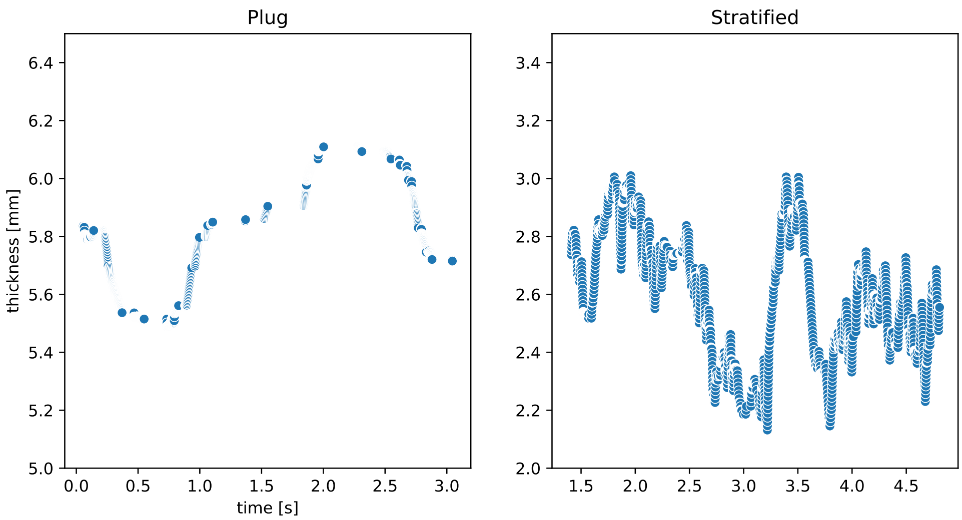

Figure 3. Flow profiles in 12 mm squared channel

The stratified flow has $j_l = 0.03$ m/s and $j_g = 2.06$ m/s. It has a lower liquid column than the plug flow, which is expected due to lower the liquid velocity. Worth noting is that this is a stratified-wavy flow, as there are several waves, evidenced by the frequent change in thickness. Also, different from the plug flow profile, there are almost no discontinuities, which is evidenced by the higher number of overlapping markers in the plot.

Figure 4 shows the probability density function for each profile. The two left most plot are relative to plug flow, while the two on the right are for the stratified one. In the two high most plots, the discontinuities on the measurement received the value 12 mm, which is the height of the tube, while on the two plots below, the discontinuities were removed. It is perceivable that the plug flows has a very distinct pattern, with considerably more discontinuities (liquid plug passing), and the liquid thickness does not concentrate on a single value, as expected, because the gas bubbles have varying shapes. On the other hand, the stratified flow has a few discontinuities, probably caused by high angles during the passage of a wave. It is also seen that the thickness focuses on a small interval of thickness, with the lower and higher values being attributed to the passing waves.

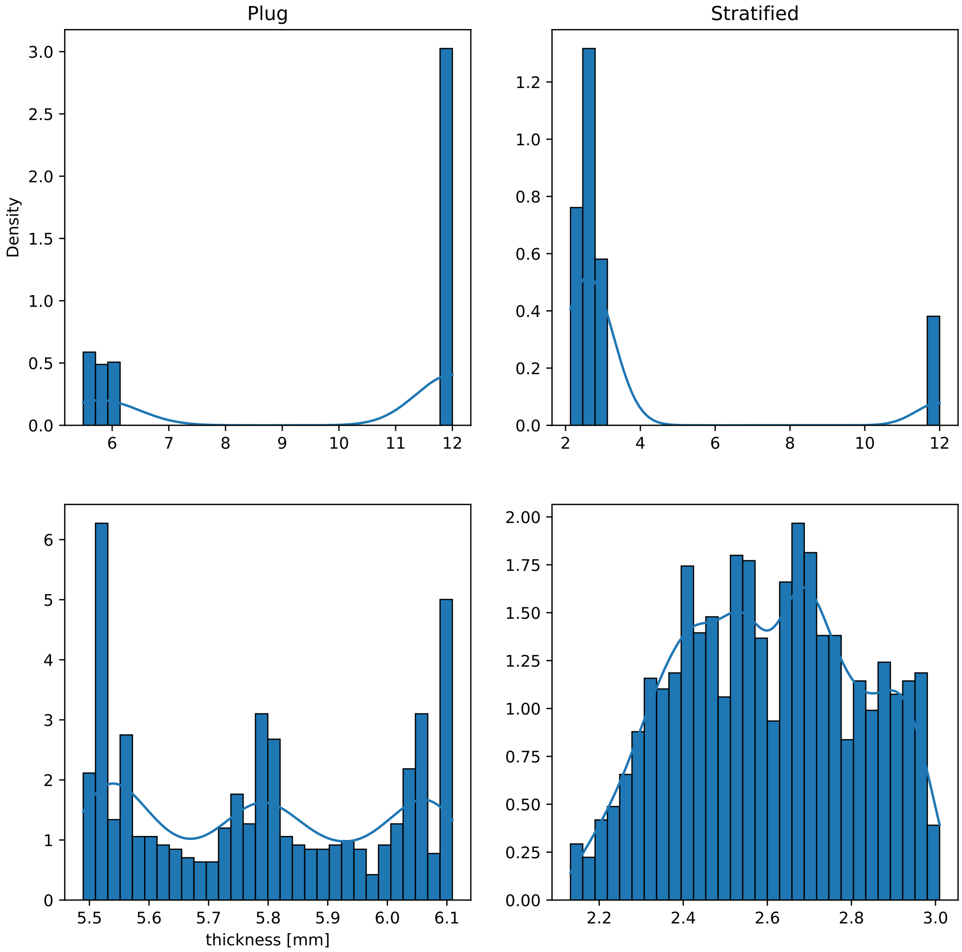

Figure 4. Probability density function for flows in 12 mm squared channel

For the 6.40$\times$ 5.0 mm^2 $(b \times h)$ section, two intermittent flows were evaluated. Figure 5 shows the first one, with $j_l = 0.2$ m/s and $j_g = 2.3$ m/s, while Fig. 6 shows the second, with $j_l = 0.4$ m/s and $j_g = 2.3$ m/s. Following the trend of the plots for the bigger channel, each flow has three plots, one with the profile, and two with the PDF, one substituting missing values with 5 mm (the height of the channel), and the other removing the discontinuities.

The left most plot of each flow shows the profile. Due to the very low liquid velocity on the slower flow, most of the it consists of big confined gas bubbles, that is why several values of thickness are zero (no liquid in the cross-section at the moment). By doubling the liquid velocity, the bubbles get smaller, and with more diverse patterns, becoming a typical

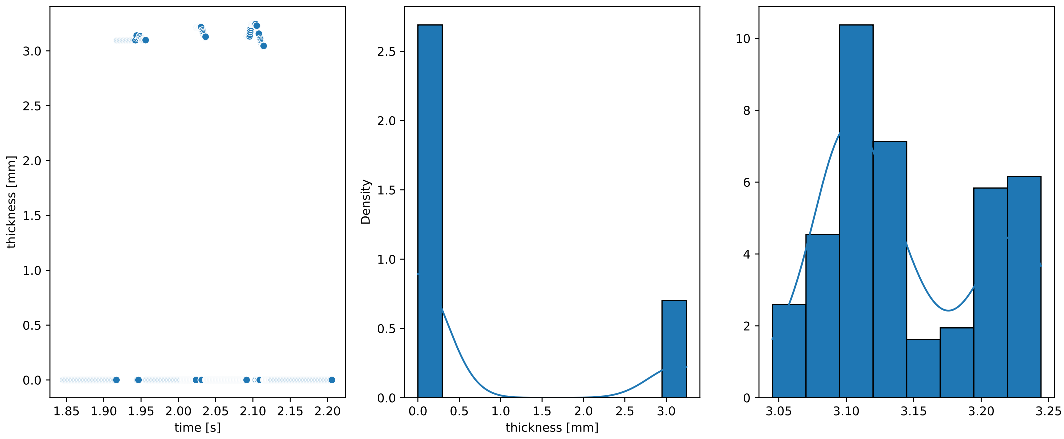

Figure 5. Flow in smaller channel - $j_l = 0.2$ m/s and $j_g = 2.3$ m/s

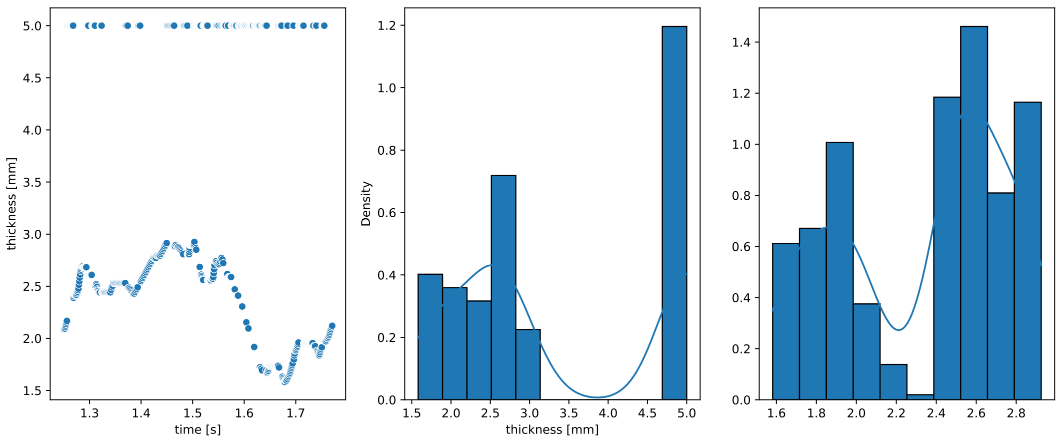

Figure 6. Flow in the smaller channel - $j_l = 0.4$ m/s and $j_g = 2.3$ m/s

plug flow. It should be noted that while its profile might look like a single bubble, there are several discontinuities, with indicates a higher number of bubbles per time.

The other two plots (middle and right one), depicts the PDF for the signal. For the slower flow, the thickness varies little, and the signal is well contained in a small interval. Also there is higher proportion of discontinuities, indicating that liquid plugs are more common than gas bubbles. The faster flow is different, displaying more values of thickness. It is different from stratified flows, as the thickness do not concentrate on any single value, rather being well distributed.

4. CONCLUSION

The probability density function of the signal obtained by the chromatic confocal microscope can be used to classify separated flow patterns. The technique was tested for stratified and several types on intermittent flows, on two different test sections. Findings include:

- Stratified flows profile have almost discontinuity-less profiles, with PDF concentrating on a single thickness value.
- Intermittent flows have a characteristic PDF, with a considerable amount of data concentrating on channel length (representing liquid plugs), and varying thickness almost homogeneously distributed.
- The PDF of confined bubbles differ from the other as it has an almost constant thickness for each liquid bubble, and zero thickness for almost all flow.

5. ACKNOWLEDGEMENTS

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