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VOID FRACTION MEASUREMENT IN STRATIFIED FLOW USING CONFOCAL CHROMATIC TECHNIQUE

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Abstract. *Cross-sectional void fraction is an important parameter in two-phase flow. The most common way to measure it is through the volumetric void fraction, using quick-closing valves. Although common, this method has drawbacks. Other methods exists, with varying degree of success and applicability. In this paper, a novel method to estimate the void fraction is proposed, using a confocal chromatic sensor. The method was validated with new experimental data of horizontal air-water stratified-flow. Experimental conditions ranged from* $j_l = 0.0550 - 0.1307\,\mathrm{m/s}$ *and* $j_g = 0.1250\,\mathrm{m/s}$. *The channel is squared with side of* $12\,\mathrm{mm}$ *and made of aluminum. Experimental trends were consistent. Eleven correlations were tested and most under-predicted the data. Lockhart and Martinelli (1949) performed best with MRD of* -0.036.

Keywords: *void fraction, confocal chromatic, two-phase flow, air-water*

1. INTRODUCTION

The void fraction is one of the most important parameters in two-phase flow, being used to calculate virtually all others parameters of interest, such as true velocity of the phases, mean properties, pressure drop, flow pattern, and others. It is defined for a point, a line, a cross-section and a volume. The cross-sectional version is the most usual, being defined as the ratio of the cross-sectional areas of the gas-phase and the entire flow.

One of the most common ways to measure void fraction consists of trapping the flow using two quick-closing valves, and estimate it as the ratio of the gas and total volumes. Some variations exists, such as draining and measuring the liquid mass and estimating its volume (Abdul-Majeed, 1996). In short, it consists of estimating the cross-sectional void fraction as the volumetric one. These methods works well for adiabatic flows in conventional channels; however, it has drawbacks for flows with phase-change as void fraction varies with length, or for mini- and micro-channels, as uncertainty becomes too high.

Other methods exists, with different applicability. Triplett *et al.* (1999) measured void fraction in micro-channels through through photo analysis. Jassim *et al.* (2007, 2008) used an web camera and a stripped background and devised a software for automatic photo analysis in mini-channels. Setyawan *et al.* (2019) estimated the void fraction in annular flow using the liquid film profile measure with 8 conductance sensors with good results in a 26 mm pipe. He *et al.* (2019) developed a multi-wire mesh capacitance probe to measure void fraction in a 50 mm pipe. In this paper, we propose a novel, non-invasive method for measuring void fraction in stratified flows, using a confocal chromatic sensor.

2. VOID FRACTION PREDICTION

Void fraction can be estimated through a plethora of correlations available in the literature. Woldesemayat and Ghajar (2007) reviewed 68 correlations using a database of mainly adiabatic, air-water flow, in conventional channels through different orientations. More recently, Xu and Fang (2014) reviewed 41 correlations, for a database consisting mainly R134a and R410A in mini-channels, for all heat transfer modes. As usual in the literature, the correlations can be divided in five categories.

The most basic model for estimating the void fraction is the homogeneous model. It assumes that both phases have the same velocity. The following equations can be deducted:

$$\alpha_h = \frac{j_g}{j} = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)\right]^{-1} \tag{1}$$

The second model is based on the slip ratio ($Sl = u_g/u_l$). Butterworth (1975) evaluated 4 correlations and noted that they might be written as:

$$\alpha = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right) Sl\right]^{-1} \quad (2)$$

The correlations of this model estimates the slip ratio in terms of other physical properties and flow parameters.
The third model is in the form $\alpha = K\alpha_h$. Bankoff (1960) named the term K and proposed it depended on the pressure.
Zuber and Findlay (1965) proposed the fourth model, in the form of:

$$\alpha = \frac{j_g}{C_0 j + u_{gj}} = \frac{x/\rho_g}{C_0\left[\frac{(1-x)}{\rho_l} + \frac{x}{\rho_g}\right] + \frac{u_{gj}}{G}} \quad (3)$$

C_0 is called distribution parameter and $u_{gj} = u_g - j$ is the gas drift velocity.
Some correlations cannot be classified as presented. Most of them are functions of the Martinelli parameter (X). Table 1 presents the correlations used in this paper.

Table 1. Void fraction correlations

Author	Correlation
Slip ratio	
Lockhart and Martinelli (1949)	$Sl = 0.28\left(\frac{1-x}{x}\right)^{-0.361}\left(\frac{\rho_g}{\rho_l}\right)^{-0.645}\left(\frac{\mu_l}{\mu_g}\right)^{0.071}$
Zivi (1964)	$Sl = (\rho_g/\rho_l)^{-1/3}$
Premoli *et al.* (1970)	$Sl = 1 + E_1\left[\left(\frac{y}{1+yE_2}\right) - yE_2\right]^{0.5}, \; E_1 = 1.578Re_{lo}^{-0.19}\left(\frac{\rho_l}{\rho_g}\right)^{0.22}$
	$E_2 = 0.0273We_{lo}Re_{lo}^{-0.51}\left(\frac{\rho_l}{\rho_g}\right)^{-0.08}, y = \frac{\alpha_h}{1-\alpha_h}$
Kanizawa and Ribatski (2015)	$Sl = 1.021Fr_{\Delta\rho}^{-0.092}\left(\frac{1-x}{x}\right)^{-\frac{1}{3}}\left(\frac{\rho_g}{\rho_l}\right)^{-\frac{2}{3}}\left(\frac{\mu_l}{\mu_g}\right)^{-0.368}, \quad \text{if } \theta = 0°$
	$Fr_{\Delta\rho} = G^2\left[(\rho_l-\rho_g)^2 gD\right]^{-1}$
Tibiriçá *et al.* (2017)	$Sl = 1.2364Fr_{\Delta\rho}^{-0.1082}\left(\frac{\rho_g}{\rho_l}\right)^{-0.31}\left(\frac{1-x}{x}\right)^{-0.267}$
$K\alpha_h$	
Hughmark (1962)	$K = \begin{cases} -0.16367 + 0.31037Z - 0.03525Z^2 + 0.0013667Z^3, & \text{if } Z < 10 \\ 0.75545 + 0.00358Z - 0.1436\times10^{-4}Z^2, & \text{if } Z \geq 10 \end{cases}$
	$Z = \left[\frac{GD}{\mu_l(1-\alpha)+\mu_g\alpha}\right]^{1/6}\left[\frac{G^2x^2}{gD{\rho_g}^2{\alpha_h}^2}\frac{1}{(1-\alpha_h)^2}\right]^{1/8}$
Drift Flux	
Rouhani and Axelsson (1970)	$C_0 = 1.1; u_{gj} = 1.18(1-x)\left[\frac{g\sigma(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$
Steiner (1993)	$C_0 = 1 + 0.12(1-x), u_{gj} = 1.18(1-x)\left[\frac{g\sigma(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$
Woldesemayat and Ghajar (2007)	$C_0 = \frac{j_g}{j}\left[1 + \left(\frac{j_l}{j_g}\right)^{(\rho_g/\rho_l)^{0.1}}\right]$
	$u_{gj} = 2.9\left[\frac{gD\sigma(1+\cos\theta)(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}(1.22 + 1.22\sin\theta)^{\left(\frac{p_o}{p}\right)}$
Miscellaneous	
Cioncolini and Thome (2012)	$\alpha = \frac{hx^n}{(1+(h-1)x^n}, \quad \begin{cases} h = -2.129 + 3.129(\rho_g/\rho_l)^{-0.2186} \\ n = 0.3487 + 0.6513(\rho_g/\rho_l)^{0.5150} \end{cases}$

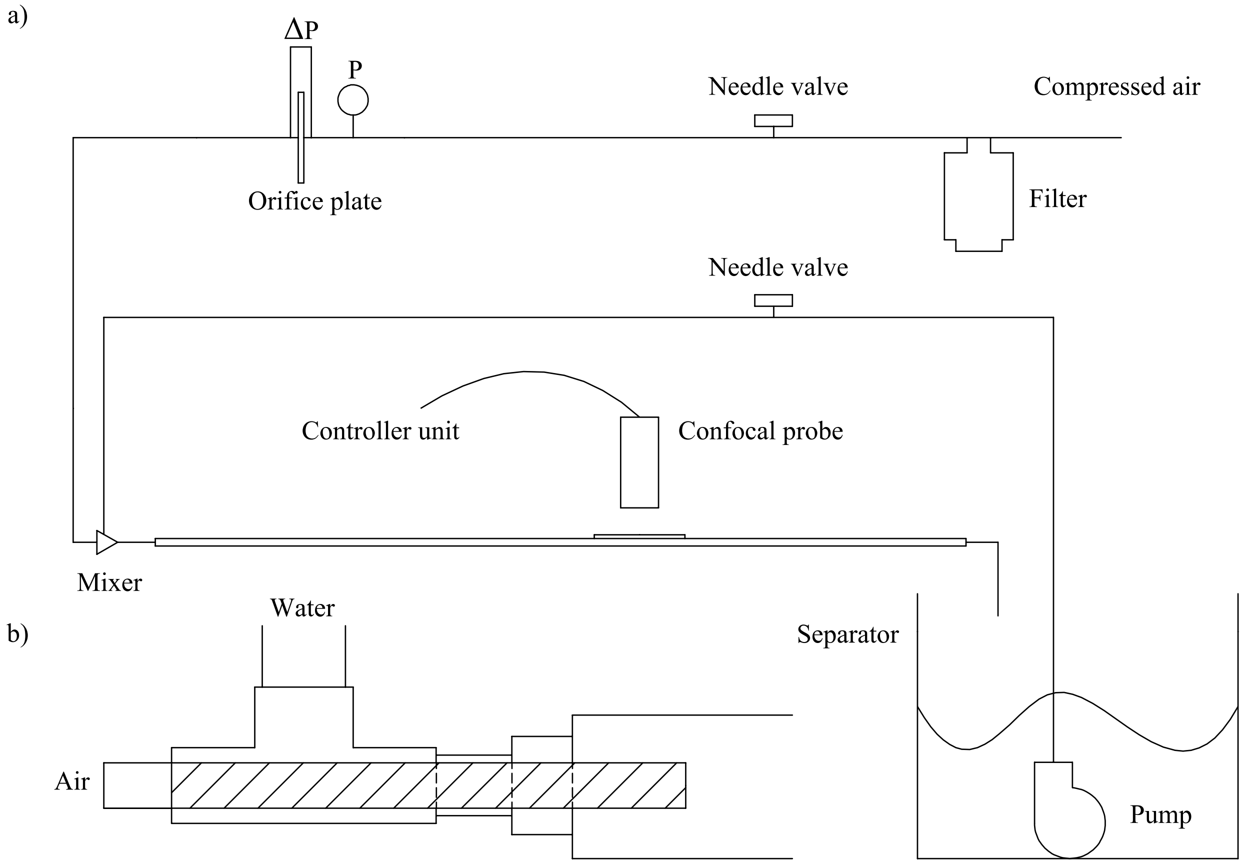

Figure 1. a) Experimental rig schematic b) Mixer

3. METHODOLOGY

Figure 1. a) shows an schematic of the experimental rig. In the gas line, compressed air flows through a filter, then the the volumetric flow rate is adjusted using a needle valve. The air mass flow is measured using an orifice plate and absolute and differential pressure transducers. In the liquid line, water from the tank is pumped, and its flow rate is controlled using a needle valve. The water mass flow rate was obtained through direct weighing, using a separate recipient, in order to reduce uncertainty. Temperature was kept constant at 18.5 °C. Experimental runs consisted of three points with a constant j_g of $0.1250\,\mathrm{m/s}$ and j_l varying from 0.055 to $0.1296\,\mathrm{m/s}$. All data was obtained for stratified flow pattern. Uncertainties are ± 5 % for j_g, ± 1 % for j_l and ± 1 °C for temperature.

Figure 1.b) shows the mixer. The water enters the T-junction vertically and is forced to go to the test section, as the other exit is sealed with the air hose and silicone. The air hose enters a T-junction, going all the way to inside the test section. 10 mm into the test section, the hose finish and air flows atop the water, mixing already in stratified pattern.

The test section consist of an aluminum, squared tube of side 12 mm and length 1.5 m. At 0.9 m, an acrylic visor with 3 mm thickness was installed, allowing for flow observation. The distance sensor functioning and details are explained below.

3.1 Void fraction measurement

Confocal chromatic means that two or more lenses have the same focus. This principle is used for a new, optic sensor, used for distance and thickness measurement. Figure 2 shows the sensor schematic. A light source emits white light that is focused in a fiber optic cable and transmitted to the optical unit. This white light then passes a set of lenses, scattering in all different wavelengths of the spectrum. All color are then focused in the same axis. If an object is inserted in this focal axis, light of a corresponding wavelength will reflect back to the sensor. A pinhole at the tip of the optical unit allows for focal-only reflections to enter the fiber optic cable. The reflected light goes to a spectrometer, identifying the wavelength, which is uniquely associated with a focal position (distance) through manufacturer's calibration.

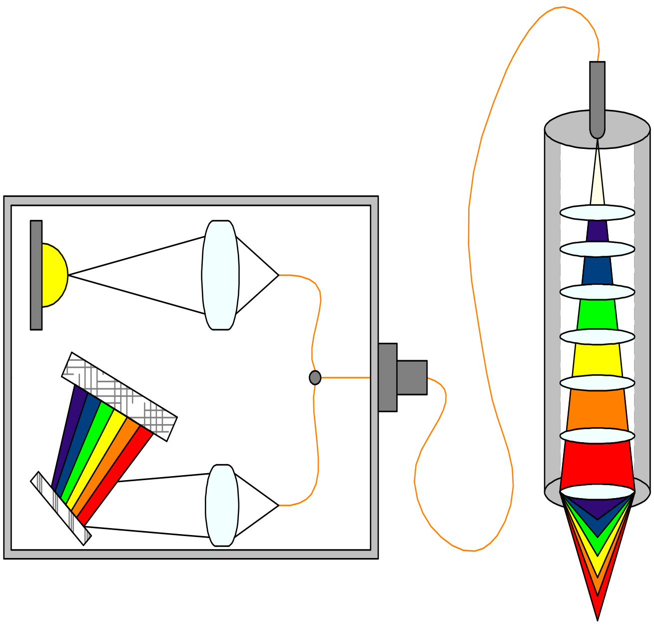

Figure 2. Confocal chromatic schematic

The light only reflects when there is a change in the optic behavior of the material. Thus, the sensor detects only interfaces. For transparent materials, this principle is used to measure distance or thickness. This can be readily applied to stratified flows to measure the the gas column. Figure 3 depicts the procedure used to measure the void fraction.

Considering a square tube with side a and gas column $h_g(t)$, the mean gas column is given by:

$$\bar{h}_g = \frac{1}{t}\int_0^t h_g(t)\,\mathrm{d}t \tag{4}$$

For a stratified flow in a rectangular cross-section, the mean cordal void fraction is the the same in whichever position it is measured. This does not hold true near the walls, but the tube is too large for it to have any meaningful effect. Then:

$$\alpha = \frac{\bar{h}_g}{a} \tag{5}$$

The confocal chromatic sensor measures $h_g(t)$. Each experimental run lasts for at least 5 s, to account for any instability. Data was collected at approximately 800 Hz. The acquisition rate can go up to 20 kHz, but it was not needed for the application, as stratified flows are well-behaved. Measurements were taken in the line of symmetry, to minimize wall effects. The sensor has a measuring range of 10 mm and spacial resolution of 60 nm with a uncertainty of 2.5 µm on thickness measurement. No systematic analysis was performed on the uncertainty. It is known that it increases with vibration; yet, for a still test section, its effects are significantly lower than the uncertainty of the flow meters.

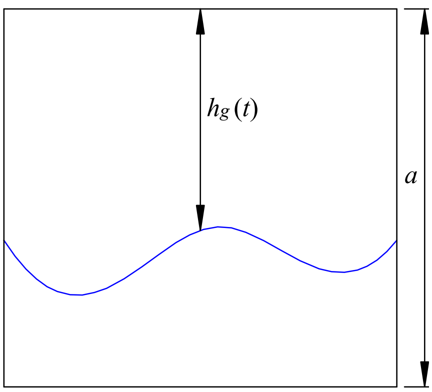

Figure 3. Void fraction measurement principle

4. RESULTS

Figure 4 shows the liquid profile for a $j_g = 0.1250\,\mathrm{m/s}$. It is interesting to notice, that as j_l increase, the profile becomes more irregular. This happens because the increase in j_l reduces the void fraction, and for a constant j_g, this is compensated by a rise in the mean gas velocity.

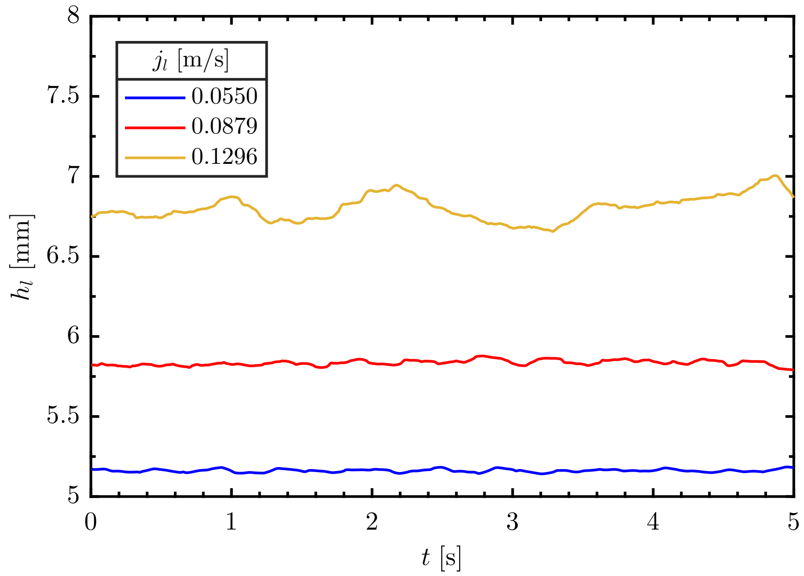

Figure 4. Liquid profile for $j_g = 0.1250\,\mathrm{m/s}$

Table 2 compares the performance of the correlations. Lockhart and Martinelli (1949) correlation performed best. This is expected, since it is a separated flow model. Zivi (1964) correlation, however, performed worse, as it is a correlation for annular flow. The homogeneous model and correlations of Cioncolini and Thome (2012) and Tibiriçá *et al.* (2017) also performed very well. In general, most correlations under-predicted the void fraction.

Table 2. Performance of the correlations

Correlation	MRD
Homogeneous	0.080
Lockhart and Martinelli (1949)	−0.036
Hughmark (1962)	−0.164
Zivi (1964)	−0.368
Premoli *et al.* (1970)	−0.197
Rouhani and Axelsson (1970)	−0.210
Steiner (1993)	−0.213
Woldesemayat and Ghajar (2007)	−0.226
Cioncolini and Thome (2012)	0.045
Kanizawa and Ribatski (2015)	−0.189
Tibiriçá *et al.* (2017)	0.049

Figure 5 shows the experimental data and top correlations for a constant gas superficial velocity of $0.1250\,\mathrm{m/s}$. Experimental trends agreed well with all empirical models, with void fraction decreasing as superficial liquid velocity increased.

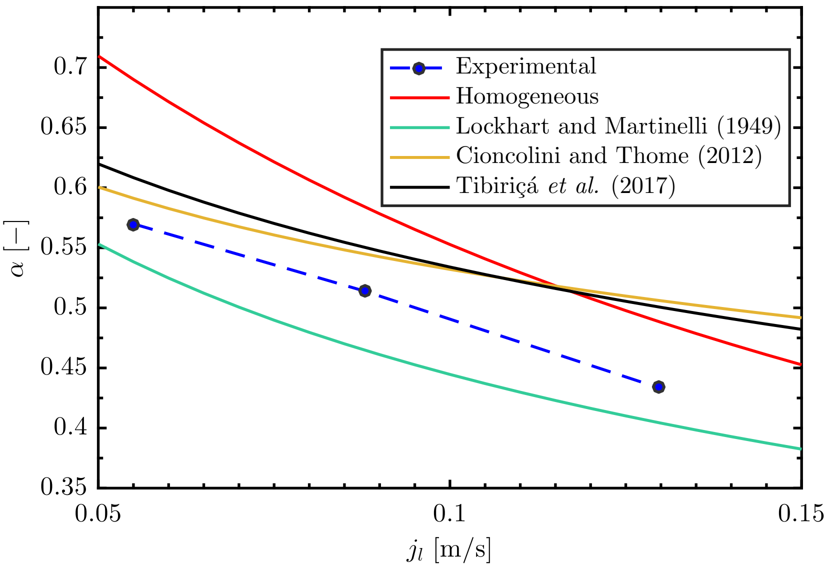

Figure 5. Void fraction for $j_g = 0.1250\,\mathrm{m/s}$

5. CONCLUSIONS

In this paper a new, non-invasive method for measuring void fraction was devised. The method consists of a confocal chromatic measuring of the instantaneous chordal void fraction, and approximating its time-averaged value to the time-averaged cross-sectional void fraction. The method is validated to air-water stratified flows in rectangular horizontal channels. New experimental data was obtained and compared with 11 correlations of the literature. Lockhart and Martinelli (1949) had the best agreement with the data, with MRD of −0.036.

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