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Experimental determination of void fraction in air-water flows using chromatic confocal microscopy

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Abstract. *Two-phase flows have use in several fields, including refrigeration and oil and gas industries. In design of heat exchangers or pipe design, parameters such as pressure drop gradient and heat transfer are very important. Such quantities depend on the operative conditions, such as mass flow, temperature, fluids, and others. Some parameters, as void fraction, are also very important, but not so easily modelled, thus experimental results are necessary to devise new experimental correlations. In this paper, new void fraction experimental results will be obtained, for horizontal air-water flows, in rectangular test sections of* $5 \times 6.4\,mm^2$ *and* $12 \times 12\,mm^2$*. The void fraction will be measured using the confocal chromatic microscopy, which is a novel technique that allows for local, precise thickness measurements in transparent mediums, used mostly in health sciences. Results are compared with empirical correlations, to good agreement.*

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

1. INTRODUCTION

Two-phase flows gave several applications, ranging from refrigeration systems to power generations and in oil and gas industries. In design problems, calculating pressure drop and heat transfer is very important. Those parameters depends on several parameters, such as mass flow and pressure, and also void fraction. Void fraction is defined as the ratio of the cross-sectional area occupied by the gas phase, by the total cross-sectional area. This parameter also depends on several others, being usually estimated through semi-empirical correlations.

Void fraction can be measured in several different ways. The first and most common is using quick closing valves. In this, the fluid is trapped and the mass (or volume)of liquid is measured, which indirectly allows to measure the gas area. While this is a volumetric measurement, for small volumes it is equivalent to the mean void fraction. Other methods exists, but are usually dependant of the flow pattern.

This paper propose a new void fraction measurement technique, applicable to separated flows. A chromatic confocal microscopy is used to obtain the local flow profile, and the void fraction is calculated integrating the gas area. For that, stratified and plug flow patterns are evaluated in horizontal air-water flows, using a rectangular $6.40\times\ 5.0\,\mathrm{mm}^2$ $(b \times h)$ and a squared $12 \times 12\,\mathrm{mm}^2$ test sections.

2. LITERATURE REVIEW

Void fraction models can be divided in homogeneous plus four other categories. Equation 1 shows the homogeneous model. It assumes that both phases have the same velocity, and can be deducted analytically.

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

The second model uses the slip ratio. (Butterworth, 1975) evaluated six void fraction correlations and noted that they could be written as functions of the slip ratio ($S = u_g/u_l$), as in Eq. 2. The slip ratio is given by empirical correlations.

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

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:

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

C_0 is called distribution parameter and $u_{gj} = u_g - j$ is the gas drift velocity. The inverse of the distribution parameter is also Bankoff (1960) parameter K.

Some correlations can not be assigned to any of those above, and thus are denominated miscellaneous.

Table 1 shows some correlations divided by model.

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)	$K = \begin{cases} -0.16367 + 0.31037Z - 0.03525Z^2 + 0.0013667Z^3, & \text{if } Z < 10 \\ 0.75545 + 0.00358Z - 0.1436 \times 10^{-4}Z^2, & \text{if } Z \geq 10 \end{cases}$
	$Z = \left[\frac{GD}{\mu_l(1-\alpha) + \mu_g\alpha}\right]^{1/6}\left[\frac{G^2x^2}{gD{\rho_g}^2{\alpha_h}^2}\frac{1}{(1-\alpha_h)^2}\right]^{1/8}$
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)	$\alpha = \frac{hx^n}{(1+(h-1)x^n)}, \quad \begin{cases} h = -2.129 + 3.129(\rho_g/\rho_l)^{-0.2186} \\ n = 0.3487 + 0.6513(\rho_g/\rho_l)^{0.5150} \end{cases}$

3. METHODOLOGY

Figure 1 shows the schematic of the experimental rig used. It consists of a line of compressed air and one of water. The compressed air has a precision pressure regulator and a ball valve for flow rate adjustment, and a orifice plate with a differential and absolute pressure sensor to measure mass flow. The water line consists of a tank, a pump, turbine flow rate meter and needle valves. The two lines enter a mixer at the inlet of the section. Exiting the test section the fluids enter a separator where the air goes to the atmosphere and the liquid return to the tank.

Two test sections were used, both with 150 cm length. The first is a squared $12 \times 12\,\text{mm}^2$ 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 $6.40\times 5.0\,\text{mm}^2$ $(b \times h)$. 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.

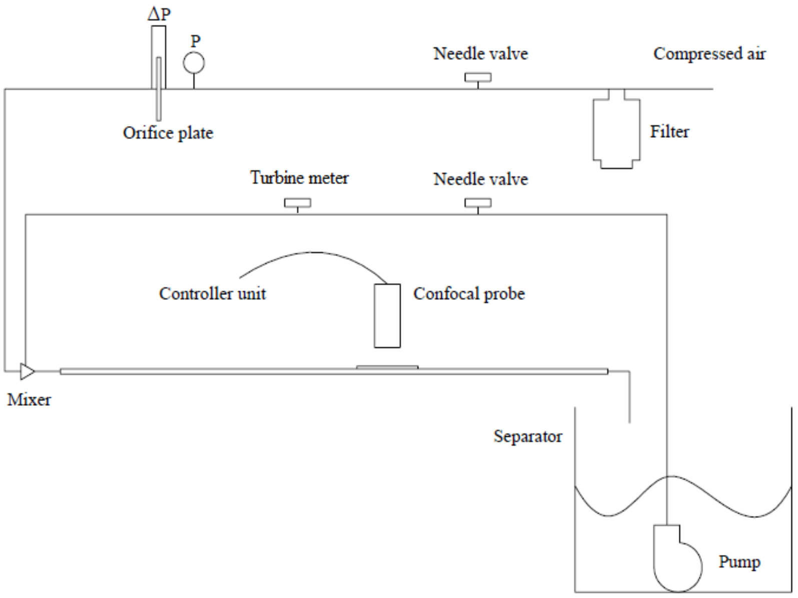

Figure 1. Experimental rig schematic

3.1 Confocal chromatic microscopy

Confocal chromatic microscopy is a novel technique, usually applied in physics and biology fields. Figure shows the schematic of the chromatic confocal working principle.

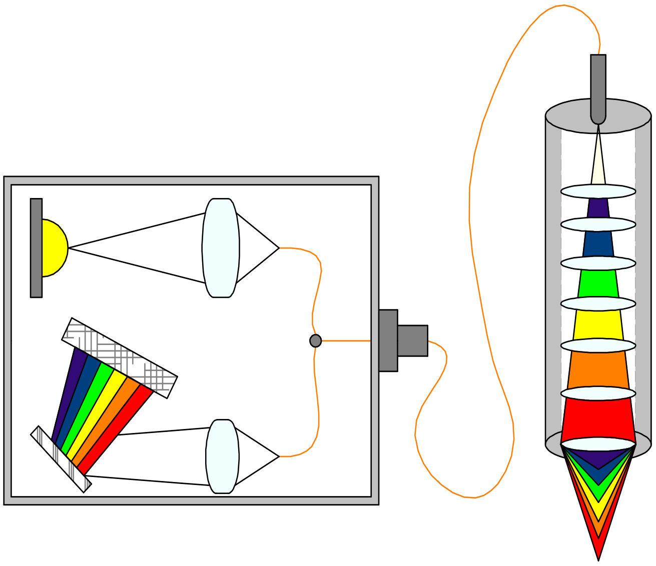

Figure 2. Confocal chromatic schematic

The light source emits white light that goes through a fiber optic cable, reaching the probe, where it passes through several lens, dispersing in all wavelengths. Those wavelengths converge in a single vertical axis. If the light that exits the probe reach an interface, it reflects back. The probe has a pinhole that allows only focal reflection, so this specific wavelength goes back through the fiber optic cable, where it goes to a spectrometer, that measures the wavelength. The sensor then convert through factory calibration the wavelength in distance, as they have an one-to-one correspondence.

The sensor may also be used in transparent mediums, where the light refracts and reflects. The wavelength associated with each interface is measured, so thickness can be measured.

3.2 Signal treatment

The chromatic confocal probe has a measuring range of 10 mm, that starts 50 mm of the end of the probe. It has adjustable acquisition rate, that can be automatically adjust to the measurement. In this case, the acquisition rate was roughly 670 Hz, which corresponds to one measurement each 0.0015 s.

When measuring through different mediums, the distance must be corrected using the refractive index. If the mediums are informed, those correction are made automatically by the control units. When the sensor doesn't receive an adequate signal, it outputs −10. This can be treated simply removing the measurement, or if the value is known (ex. when there is only liquid flowing during a plug flow), it can be manually imputed.

4. RESULTS

The void fraction is calculated numerically integrating the flow profile in the following fashion:

$$\alpha = 1 - \frac{\int_{t_1}^{t_2} h_l \ \mathrm{d}t}{\int_{t_1}^{t_2} 5 \ \mathrm{d}t} \tag{4}$$

Figure 3 shows the flow profile for three stratified flows in the squared $12 \times 12\,\mathrm{mm}^2$ test section.

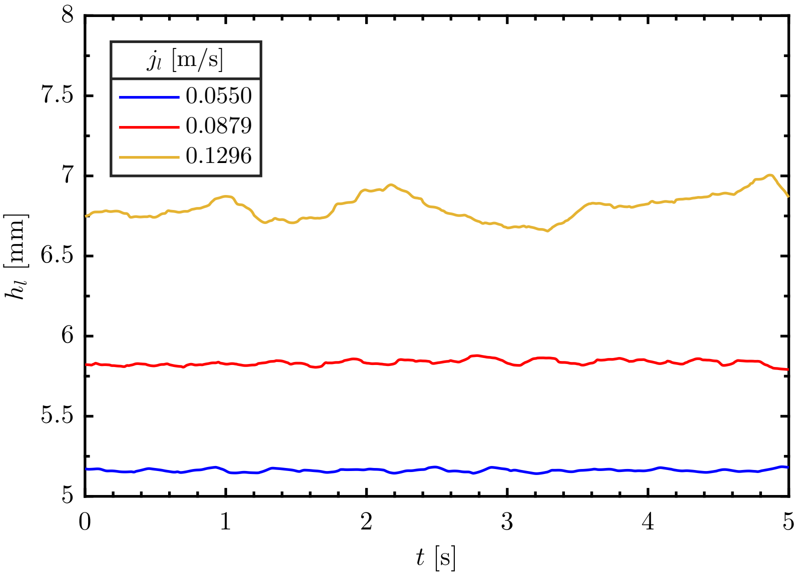

Figure 3. Liquid profile for $j_g = 0.1250\,\mathrm{m/s}$

Figure 4 shows the void fraction calculated for each of the above profiles. The experimental values are similar to the empirical correlations, corroborating to the technique validity.

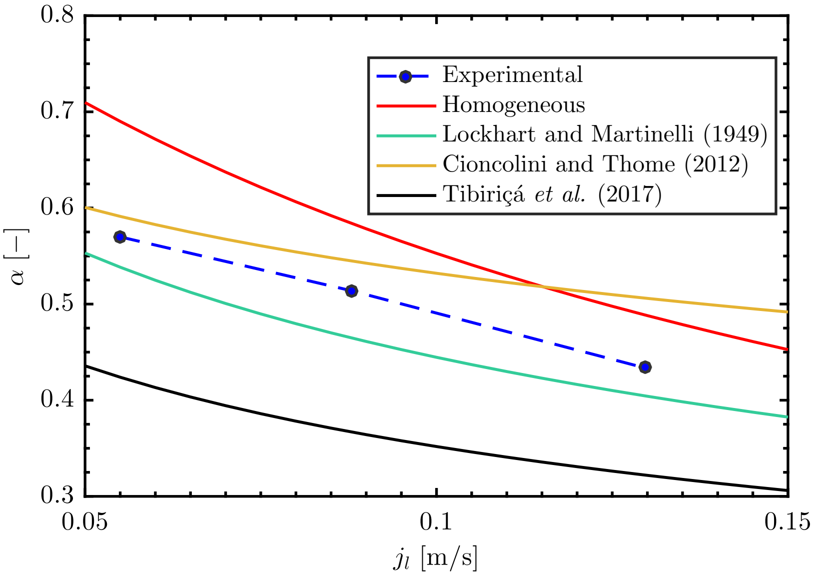

Figure 4. Void fraction for $j_g \approx 0.1250\,\mathrm{m/s}$

In the $6.40 \times 5.0\,\mathrm{mm}^2$ $(b \times h)$ test section, a plug flow with $j_l = 0.52\,\mathrm{m/s}$ and $j_g = 1.72\,\mathrm{m/s}$ was evaluated. Figure

5 shows the flow profile. There are several discontinuities, dividing the flow in two regions. One is the liquid plug flow ($\alpha = 0$), the other is when there is a passage of a gas bubble. The void fraction is then found integrating the entire profile, which is basically the mean void fraction for the entire profile. The measured value is 0.23, while the one through Zivi (1964) is 0.26.

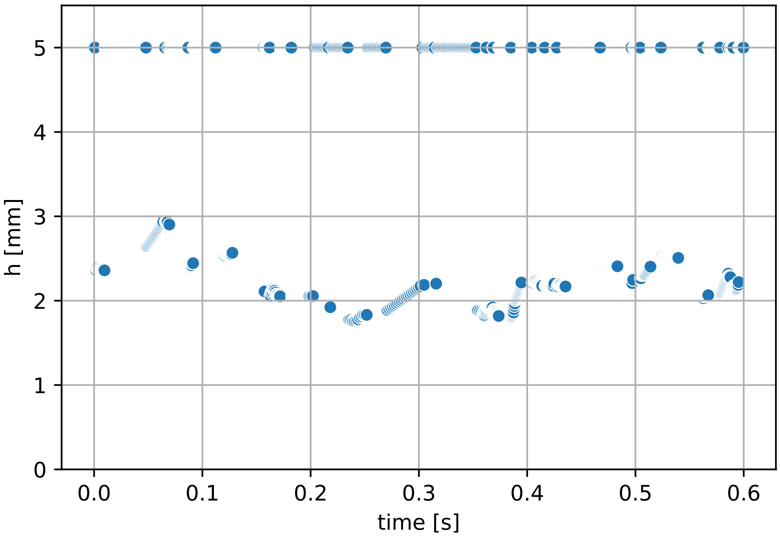

Figure 5. Void fraction for $j_l = 0.52\,\mathrm{m/s}$ and $j_g = 1.72\,\mathrm{m/s}$

5. CONCLUSIONS

Void fraction data in horizontal air-water flows was obtained integrating the local profile, measured using the chromatic confocal microscopy. To validate the technique, the measured values were compared with those obtained using empirical correlations, with good agreement. Stratified flows have a more smooth profile, which makes easier for the new technique to identify.

6. ACKNOWLEDGEMENTS

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