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# Low Cost True Monofiber Optical Probe for Local Void Fraction Measurements in Minichannels

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**Abstract.** Two phase flow inside minichannels is one of the most investigated research topic at present. The measurement of the flow rate parameters is fundamental to characterize the flow pattern and its evolution over time. This paper shows that an optical technique, well-known for large diameter pipes, can be applied to mini channels with a laminar mass flow rate. In particular, a Y-junction mono-fiber optic system with a chamfered tip probe has been built and tested. This method is applied to the local void fraction measurement in a copper capillary pipe with internal diameter of 2 mm and external diameter of 3.00 mm. Different probes have been developed and tested. The accuracy of the method depends on the size, the shape of the tip and on the tip distance from the pipe centre. Different distances and liquid flow rate have been tested. The two-phase flow pattern is also visualized and recorded by a high speed camera (FASTEC Troubleshooter 16000 fps) and post processed with an image analysis technique. A good agreement between the optical and the video signal has been observed.

## 1 Introduction

Two-phase flow prediction in minichannels is a basic very active research field at present, because of the increasing number of mini equipments in ground and space applications which involves capillary pipes. The measurement techniques of parameters as pressure, velocity, temperature, mass flow rate are well assessed at the moment even in capillary pipes. On the other hand the measurement of void fraction inside two-phase flow for minichannels is currently an unsolved problem.

The simplest measurement technique of void fraction is the quick-closing valve method, still used at present. This method traps liquid in a tube to measure mass and liquid volume [1]. Until now there are several studies concerning void fraction measurements and involving different configurations and setups. They are largely applied to large pipes [2]-[4].

Maurus et al. [5] visually observed the void fraction in a subcooled flow of boiling water through a horizontal rectangular channel. A high-speed camera's top and side views of vapor shape helped to estimate the void fraction. Bowers and Hrnjak [6] visually observed the void fraction measurement of R-134a stratified flow through three different tube diameters, 7.2, 8.7, and 15.3 mm. They stated that void fraction depended on tube size diameter, while mass velocity had little effect on it. Winkler et



al. [7] used image analysis to measure the void fraction of R-134a's condensing process while flowing through a minichannel ranging from 2.00 to 4.91 mm. Their results show that neither mass flux nor channel size had a significant effect on the void fraction of a wavy flow pattern.

The optical system based on the images acquisition has, however, a big limitation because it cannot be applied to opaque pipes. Among the void fraction measurement techniques, the employment of optical fiber probes seems to be one of the most interesting one, because of they can be applied to opaque pipes of different materials (metallic, plastic, glass), they are appropriate for a large number of working fluids and they can be used with a very high sampling rate [8]-[9]. This technique is based on the difference, in terms of refraction index, between the vapour and liquid phases where the tip of the probe is periodically immersed.

Unfortunately the fiber optic probe is an intrusive measurement because the tip is immersed in the fluid and the sensitive surface, depending on the size of the probe, could be not negligible respect the cross sectional area of the pipe. In the past it is usually applied to large ducts measurements.

In addition optical fiber probe measures the local void fraction evolution over the time of the zone where the tip is immersed, so that a big number of probes, in different points of the cross section, must be used if the flow pattern must be characterised.

However, in the case of two-phase flow pattern characterisation for mini-channels the number of probes can be drastically reduced down to one. The highly confined flow rate shows different flow patterns respect to the large channels case: patterns as slug/plug, annular and semi annular are the most frequently observed [8][11]. In annular, semi-annular and slug/plug patterns the position of the probe tip inside the cross section and its distance from the pipe centre assumes lower importance in the flow pattern characterisation.

This paper deals with the limitations and the accuracy of the application of a fiber optic technique to capillary pipes to detect the two-phase flow pattern over time. Capillary pipes are characterised by very low diameters, given by Bond number lower than 2. This configuration is typical of Pulsating Heat Pipes devices and other automotive heat exchangers.

Different probes have been built and tested in a water/air loop. The void fraction experimentally detected by the optical probe inside a copper pipe with an internal diameter of 2 mm, has been compared with that measured with an image acquisition system, showing good agreement. Some preliminary qualitative studies on the influence of the probe tip position with respect to pipe centre have been presented.

## 2 Fiber Optic void fraction measurements

The fiber optic void fraction measurement is based on the physical principle that a light beam ray passing through a transparent surface can be refracted with different angles according to medium in contact with the surface. The basic relationship between governing refraction at the interface between two media is given by the Snell's law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \quad (1)$$

where  $n_1$  and  $n_2$  are the refraction indexes of the two media and  $\theta_1$  and  $\theta_2$  are and the incidence angles of the incoming and outgoing light beam, respectively. It is interesting to note that as  $\theta_1$  decreases,  $\theta_2$  tends to 0 and the intensity of the light beam, that crosses the interface, decreases to 0, therefore the light beam is reflected back. The value of  $\theta_1$ , named  $\theta_{TIR}$  and corresponding to the total reflection, is given by the limit of  $\theta_2$  that tends to 0, so that  $\cos\theta_2 \approx 1$

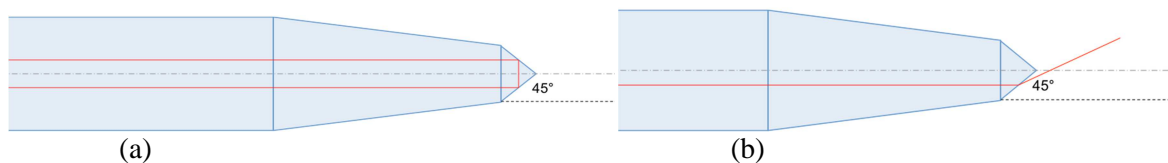
$$\theta_{TIR} = \cos^{-1} \left( \frac{n_2}{n_1} \right). \quad (2)$$

Eq(2) shows that if  $\theta_1 \leq \theta_{\text{TR}}$  the beam inside the fiber core is totally reflected, and it is completely contained inside it. This phenomenon allows optical fibers to correctly work, because the refraction index of the core is higher than the refraction index of the external cladding and, therefore, the beam is confined inside the core channel. In this method the material of the probe immersed in the fluid assumes great importance in the feasibility of the measurement.

One of the most applied probe in large pipes in the past is the *U-shaped probe*. This type of probe tip is characterized by a single optical fiber bended with a relative small curvature radius. The U-turn of the fiber is then inserted at the measurement point. This configuration is the simplest because it needs no fiber junctions or splitter, as there is only one fiber where the beam can pass. However this technique presents several disadvantages: the fiber optic must be sufficient flexible to be curved, and the probe assumes large dimensions. It cannot be applied to capillary pipes. Another probe tip is named "Joined-tip". It is characterized by a welded probe composed of two optical fibers polished and fused or joined together by means of a suitable glue or resin. This manufacturing process is shown in [12]. The tip is fixed by means of a suitable epoxy resin. This probe also has large dimensions, and it cannot be applied to capillary pipes.

The true monofiber optical probe is characterized by a single fiber section of variable length. The light beams, both the one coming from the laser source and going to the detector, pass through the same core channel and are then splitted by means of a Y- Junction.

In the past this technique has been used by Carrica et al. [13] to characterise the void fraction in a pool boiling process. Carrica et al. state that the tip of the true monofiber probe must be opportunely chamfered to obtain a back signal as the light beam impacts on the fiber external surface. An angle of  $45^\circ$  is advised. Figure 1 shows the different behaviour of the chamfered tip in case of total reflection or refraction. The beam (not necessarily parallel to the fiber axis) incident on the tip surface (interface between the two media) is partially reflected and partially refracted. The quantity of reflected light is higher when the tip is in contact with gas phase than with liquid phase.



**Figure 1:** Probe tip ideal working principle (a) gas phase (b) liquid phase

### 3 Experimental Activity

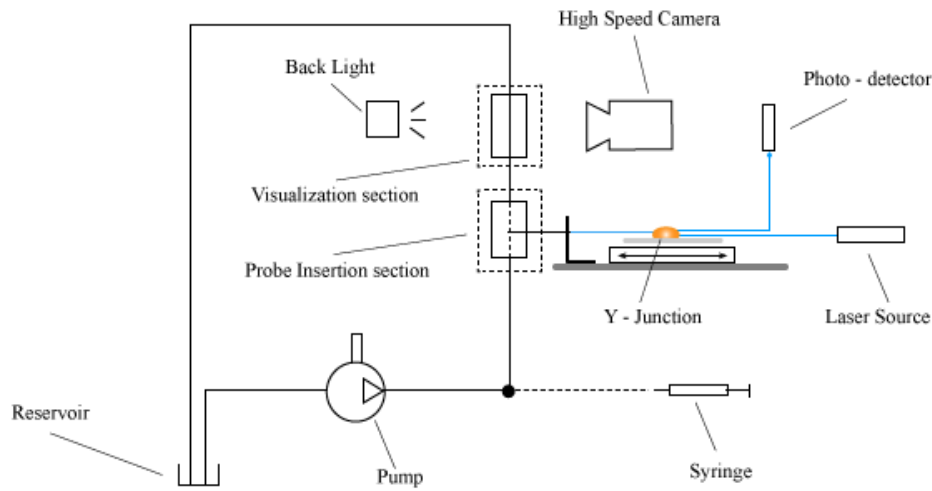
A Y-junction optical system has been built and tested inside a capillary pipe ( $D=2$  mm). The experimental facility consists of: a measurement loop, the optical fiber void fraction system and the visualization section. A scheme of the setup is shown in Figure 2.

The measurement loop consists of a reservoir, a capillary pipe loop, a pump and a syringe pump.

The materials: of the pipes are silicon, copper in the fiber optic section and glass in the visualization section.

The pump is peristaltic (ISMATECH® MCP-Z Standard Gear Pump ISM 405) with water flow rate of 1-7020 l/min.

The two phase flow pattern is created by a syringe pump pushing air into the loop with a mass flow rate up to  $5 \text{ cm}^3/\text{s}$ . The temperature of the water inside the tank is measured by a PT100 probe.



**Figure 2:** Sketch of the experimental setup

*1.1. The optical fiber measurement system*

The optical fiber system consists of: light source, fiber connections, Y-junction, tip probe, photo detector and acquisition system. The light source is a He-Ne Class 3B Laser working at 632,9  $\mu\text{m}$  with a nominal power  $P_0 < 5\text{mW}$ . The light beam coming from laser source is collimated in air into the fiber connection, that has been fixed on a stainless steel tube, placed with a ferrule clamp (FCM/M) on an optical desk.

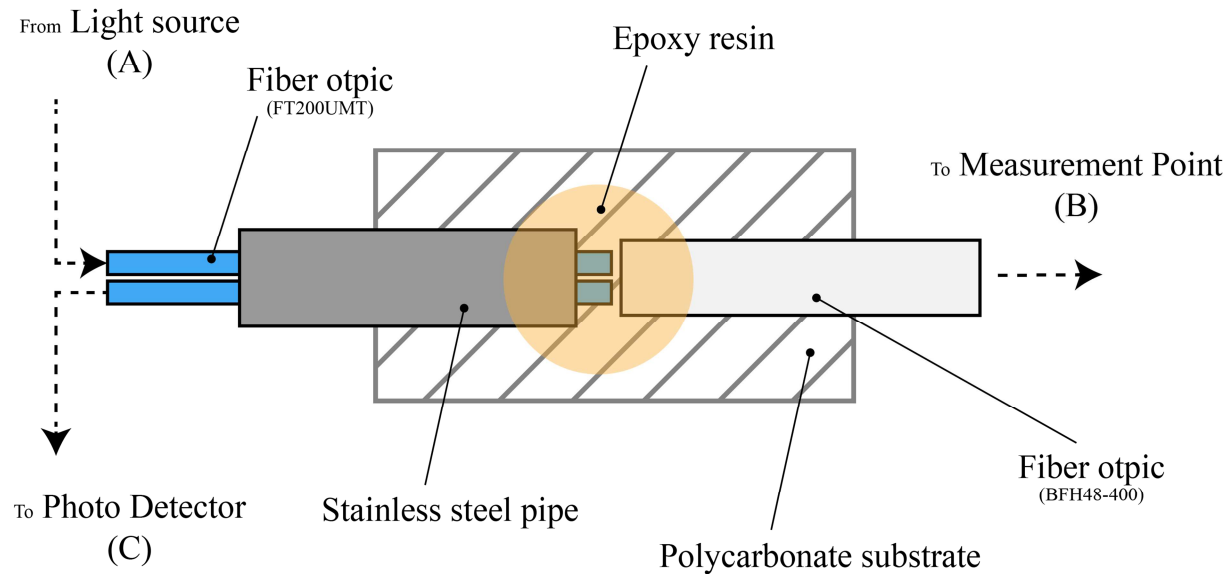
The fiber optics chosen to connect the laser source to the Y-junction and the junction with the photo detector are multimode pure slice fiber manufactured by THORSLAB® and listed in Table 1. They are characterised by high flexibility and high Numerical Aperture (N.A.).

**TABLE 1: Optical fibers employed for the probe**

Code	Range $\mu\text{m}$	Cladding diameter $\mu\text{m}$	Core diameter $\mu\text{m}$	N.A.
<b>BFH48-400</b>	300 – 1200	430	400	0,48
<b>FT200UMT</b>	300 – 1200	225	200	0,39

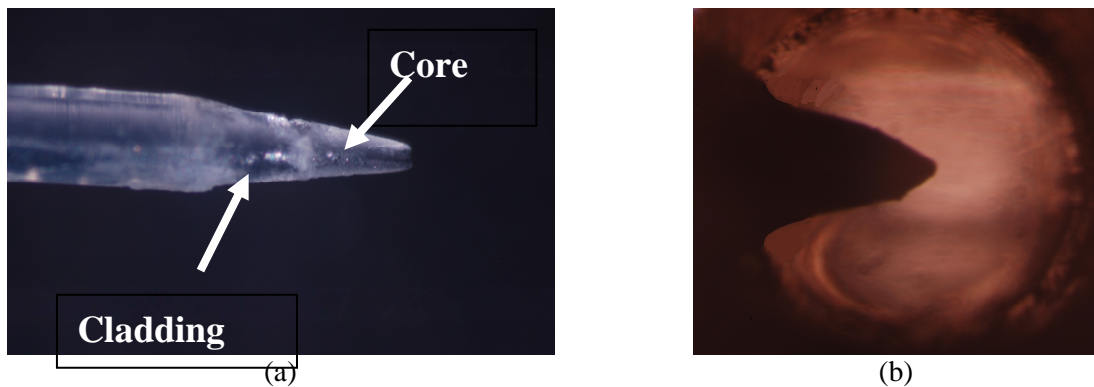
The Y-junction is the most critical part of the optical system. It conveys the light beams, coming from the source, into the monofiber probe and splits the light coming back from the probe to the photodetector. It operates as a circulator. The incorrect alignment of the fiber causes high light losses, therefore and the signal going back to the photodetector could be insufficient or very noisy. The basic scheme was proposed by Carrica et al. [ 13 ] and is shown in Figure 3.

The two fibers coming from the light source and going back to photodetector are collimated with the aid of a 20x microscope. The fibers are then placed and glued in a stainless steel micropipe. Then the two tips are cut and polished with polish paper. The same polishing procedure is used to manufacture the larger diameter fiber used for the chamfered probe. The surface finish is checked by means of a microscope , and a first signal check is performed in order to enhance fiber alignment. A bi-component resin, used for connectorizing fibers, is placed on the junction in order to fix the components and reduce losses.



**Figure 3:** Y-Junction scheme

The probe is made of a 400  $\mu\text{m}$  fiber and the tip is - chamfered at an angle of  $45^\circ$ . The fiber has not been stripped, and there was the need to remove part of the coating. The polishing procedure is the same as the junction. At first the tip has been cut to length and polished with 1000K paper, then finished with 2000K paper. During this procedure, it has been constantly checked by means of a microscope. Due to the fact the tip must fit into a minichannel, the chamfering has been extended to the section before the tip, obtaining a conical shape. An enlarged (20X) photo of the tip probe is shown in Figure 4a.

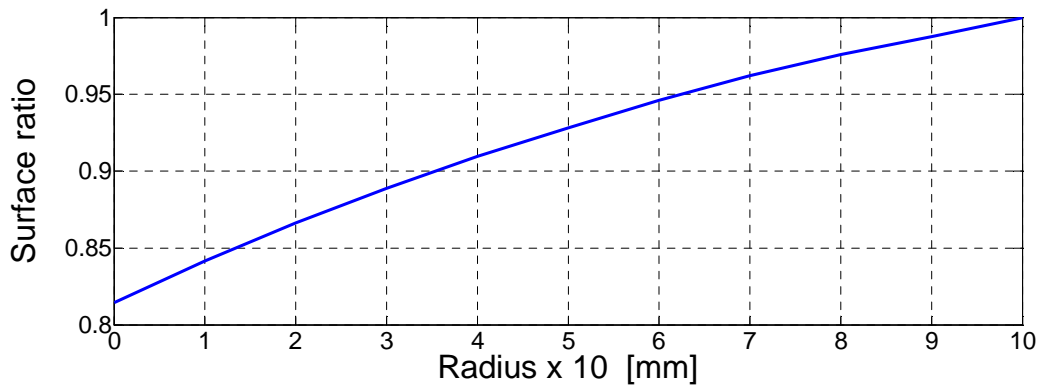


**Figure 4:** (a) Enlarged photo of the true monofiber tip probe (b) Enlarged photo of tip probe inside the pipe

The tip probe has been inserted inside the void fraction measurement cell, that consists of a copper T junction between the copper pipe (OD=3 mm, ID = 2mm) and a stainless steel pipe (OD=1 mm, ID=900  $\mu\text{m}$ ). The Y junction has been placed over a micro-regulated chassis that allows the regulation of the position of the tip inside the pipe with an accuracy of  $\pm 0.05$  mm.

The enlarged photo of the probe with the tip positioned at the pipe centre, see Figure 4b, shows that the probe is highly intrusive, and a big portion of the cross sectional area is occupied by the probe. The ratio between the surface occupied by the probe and the entire cross sectional area, versus the position of its tip along the pipe radius, is shown in Figure 5.

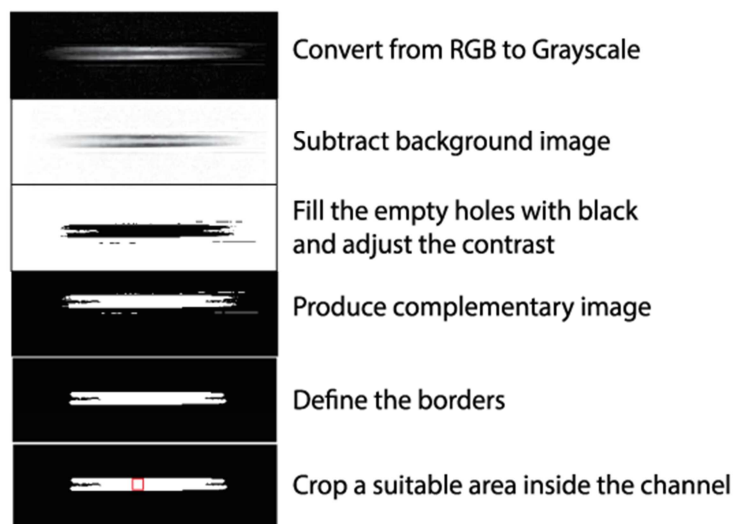
The signal coming from the photo detector has been acquired by an acquisition board Arduino ATmega328 . It has 6 analogue inputs, and features the Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter. The clock speed is 16 MHz and the acquisition sampling rate is 40 Hz.



**Figure 5:** Surface ratio vs the tip position along the radius

*1.2. Video acquisition system*

The void fraction has been detected also by acquiring a video with a high speed videocamera (FASTEC Troubleshooter HR, up to 16000 fps @ 1280x32), and post processing the collected images. The video section consists of a glass pipe (ID=2 mm) and a video camera, externally triggered to synchronize the video capture with the signal coming from the photo-detector. The back light behind the glass pipe is a white LED Source 5,5 W DC12V. It has a good light diffusion, a constant background colour and reduced reflection noise effects. The video has been taken at 125 fps with a resolution of 1280x32 pixels. The images have been post-processed as shown in Figure 6.



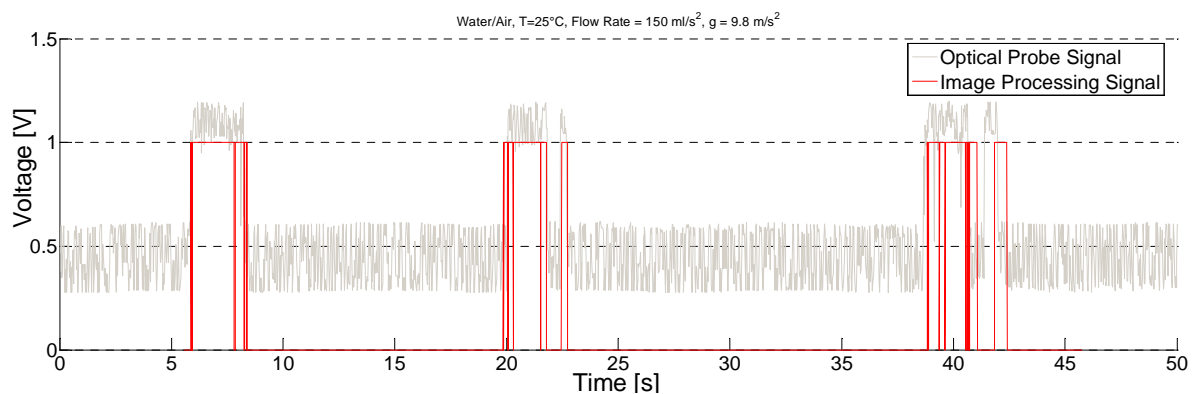
**Figure 6:** Images post-processing sequence

## 4 Results and discussion

### 4.1 Optical probe and video capture void fraction measurement

In order to understand the reliability of the fiber probe when applied to minichannels, a test has been carried out at constant water mass flow, pushing a measured volume of air, at the same temperature, into the loop, in order to obtain a two phase flow pattern. In accordance with Ong et al. [10] the water mass flow rate is 2.5 ml/s and the volume of air pushed inside the loop has been calculated to obtain a slug flow. Three different vapour slugs have been visualized.

Figure 7 shows the comparison between the optical signal with a tip probe placed at the pipe centre, with that resulting from image acquisition.



**Figure 7:** Comparison between the void fraction measured by the video capture and fiber probe

According to the Snell's law and taking into account that the refraction index  $n_1$  of the silica core is higher than the refraction index of liquid/gas, it is possible to define the critical total reflection angles of the two phases. By considering water ( $n_{\text{water}} = 1.33$ ) and air ( $n_{\text{air}} = 1$ ) and silica core ( $n_{\text{silica}} = 1.46$ ) the critical angles are 0.42 rad ( $24^\circ$ ) for water and 0.72 rad ( $41.2^\circ$ ) for air.

For this reason the quantity of light which is reflected back to the light detector is greater when the probe tip is in contact with air. Figure 7 shows with great evidence three slugs passing through the probe. The local void fraction measured by the optical probe and that obtained by image processing show a good agreement and errors lower than 12%. A good repeatability has been observed.

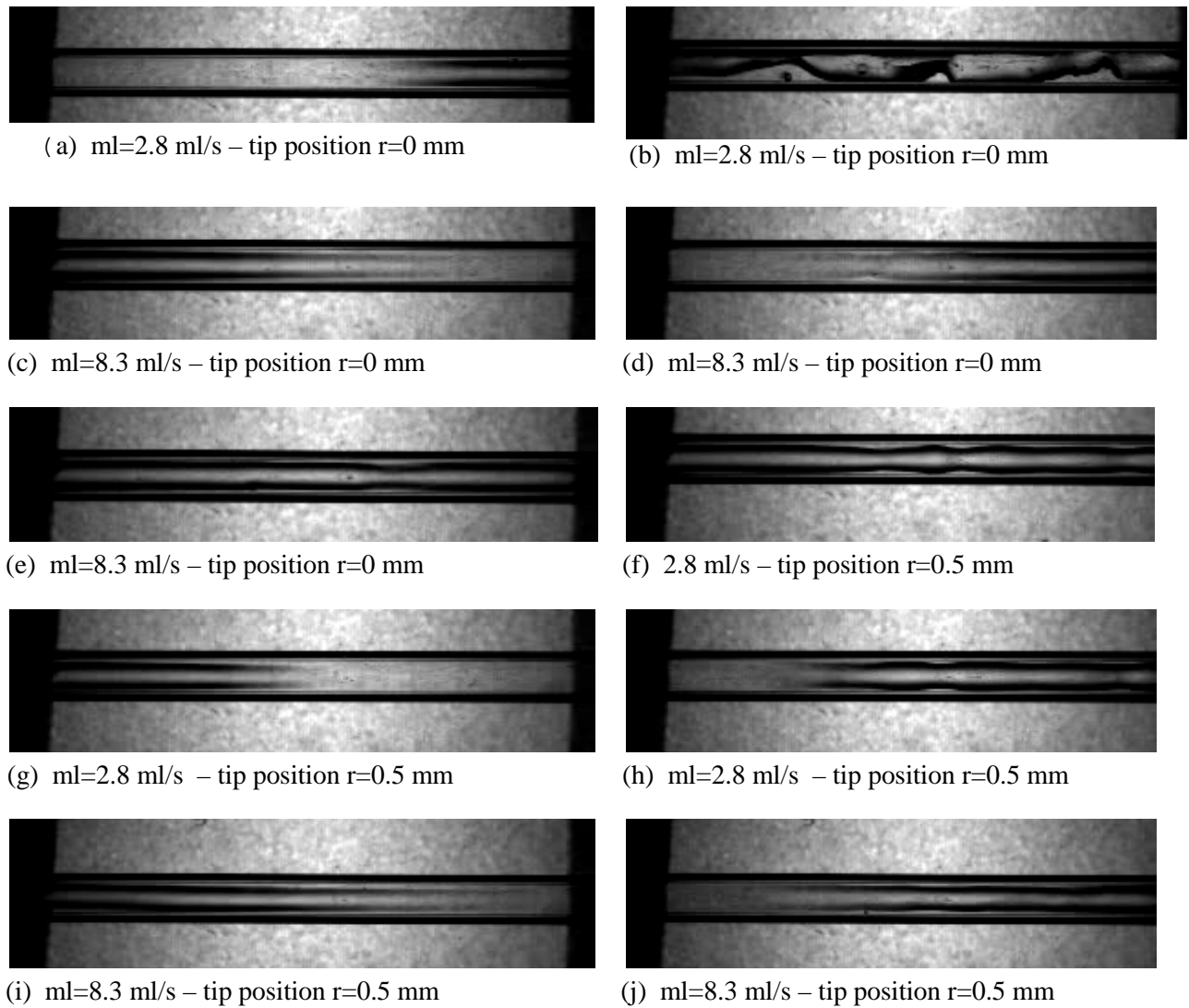
### 4.2 Preliminary test on the influence of the tip position

A preliminary experimental activity has been carried out in order to understand to what extent the optical probe can be considered intrusive in flow pattern detection. Three different tests at different liquid flow rates (2.8, 5 and 8.3 ml/s) and two radial positions of the tip probe ( $r=0$  and 5 mm) have been tested. The first position ( $r=0$  mm) corresponds to the tip placed at the pipe centre with 82% of the cross sectional area left free by the probe, the second position is with the tip placed at  $r=5$  mm (free surface of 92%). A visualization of the different flow patterns at different regimes is shown in Figure 8.

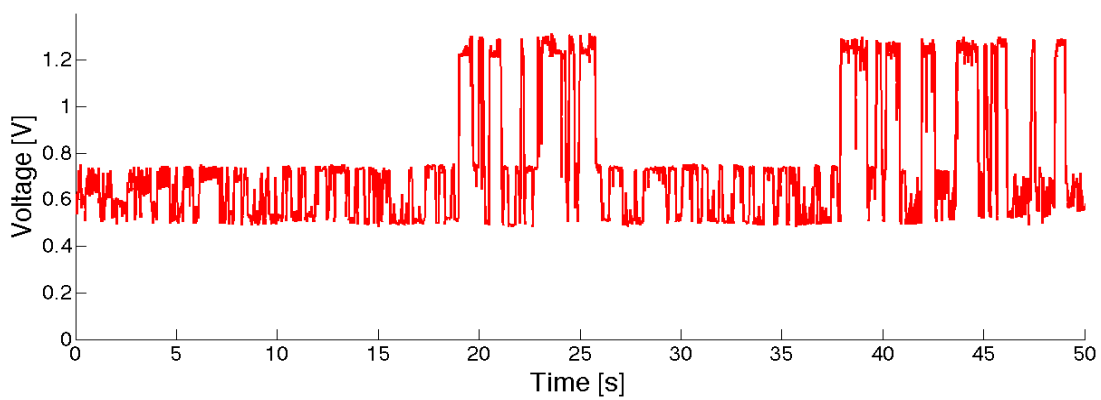
The images in figure qualitatively shows that the optical probe modifies the two-phase pattern distribution mostly at low flow rates. Figure (a) shows the end of a slug of vapour for a flow rate of 2.8 ml/s. It possible to see as the probe breaks the slug backward meniscus, and several following microbubbles can be observed. This problem is evident at high mass flow rates and even when the tip is placed at  $r=5$  mm, even if 92% of the surface is free in this case

However it is possible to note that at high flow rates and at  $r=0.5$  mm both the advancing (Figures 8c, g, i) and the receding one menisci, (Figures 8c, g, i, h) tend to be less disturbed than in the case with probe at  $r=0$  mm.



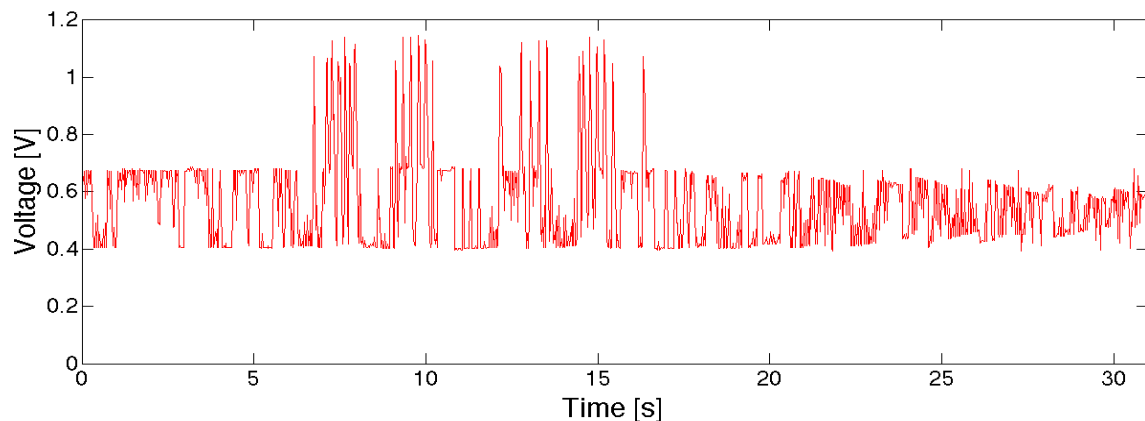


**Figure 8:** Different flow pattern at different liquid flow rate and tip radial positions



**Figure 9:** Photo-detector signal over time for the probe at r=0 mm and ml=2.8 ml/s.

Another interesting qualitative tendency, observable as the probe is receeded toward the inner surface, regards the pattern of the slug. For low flow rates (Figure 8b) the flow pattern is higly disturbed by the fiber probe, but this disturbance becomes very low as the probe is placed at  $r=5$  mm (Figure 8f, j) . Figure 9 and 10 show the voltage measured by the photo detector vs. time as two-phase flow is passing through the probe, at  $r=0$  mm and flow rate of 2.8 ml/s, and at  $r=0.5$  mm and flow rate of 8.3 ml/s, respectively.



**Figure 10:** Photo-detector signal over time for the probe at  $r=5$  mm and  $ml=8.3$  ml/s.

It is interesting to note as the probe is able to detect the flow pattern in both cases. Figure 10 shows a greater number of peaks, because the the slugs are shorter than the in the other case. The comparison between the probe signal and the void fraction calculated by the image processing has however confirmed a good agreemeent also in these two cases.

## 5 Conclusions

This paper deals with the limitations and the accuracy of the application of a fiber optic technique to detect the flow pattern over time in capillary pipes. Among the void fraction measurement techniques, the fiber optic probes can be applied to opaque pipes of different materials (metallic, plastic, glass), they can be used with a large number of working fluids with a very high sampling rate. Different probes have been built and tested in a water/air loop. The void fraction detected by the optical probe has been compared with that measured with an image acquisition system, and a good agreement has been observed (errors lower than 12%). Unfortunately the fiber optic probe is an intrusive measurement: some preliminary qualitative studies on the influence of the probe tip position with respect to pipe centre have been presented. Experimental tests have confirmed that this probe highly disturbs the flow pattern by breaking the advancing and receding menisci in slug flow. As expected, this disturbance increases when the probe is more deeply inserted along the tube diameter. Further studies will be aimed to optimize the radial position of the probe, in order to detect the void fraction making as low as possible the disturbances and modifications of the flow pattern.

## Nomenclature

$Bo$	Bond Number	
$D$	Pipe diameter	(m)
$g$	Gravity acceleration	( $m/s^2$ )
$ml$	Liquid flow rate	( $m^3/s$ )
$n$	Refraction index	(-)

$\rho_v$	Vapour density	(kg/m <sup>3</sup> )
$\rho_l$	Liquid density	(kg/m <sup>3</sup> )
$\theta$	Angle	(rad)

## References

- [1] M. Ishii, "One-Dimensional Drift-Flux Model and Constitutive Equations for Relative Motion Between Phases in Various Two-Phase Flow Regimes," Argonne National Lab Report, ANL 77-47, October 1977.
- [2] G.B. Wallis, One-Dimensional Two-Phase Flow, McGraw Hill, 2nd Edition, New York, 1979.
- [3] Srisombaa R., Mahianb O., Dalkilicc A.S., Wongwisesa S., Measurement of the void fraction of R-134a flowing through a horizontal tube International Communications in Heat and Mass Transfer Volume 56, August 2014, Pages 8–14.
- [4] S.M. Bhagwat, A.J. Ghajar A flow pattern independent drift flux model based void fraction correlation for a wide range of gas–liquid two phase flow, International Journal of Multiphase Flow 59, (2014) 186–205
- [5] R. Maurus, V. Ilchenko, T. Sattelmayer, Study of the bubble characteristics and the local void fraction in subcooled flow boiling using digital imaging and analysing techniques, Exp. Thermal Fluid Sci., 26 (2002), pp. 147–155.
- [6] C.D. Bowers, S.P. Hrnjak, Determination of void fraction in separated two-phase flows using optical techniques International Refrigeration and Air Conditioning Conference, 2010, Paper 1083 (2010).
- [7] J. Winkler, J. Killion, S. Garimella, Void fractions for condensing refrigerant flow in small channels. Part II: void fraction measurement and modeling, Int. J. Refrig., 35 (2012), pp. 246–262
- [8] B. Stankovic An experimental study on the local void fraction measurement in large diameter vertical pipes using optical probes Open Access Dissertations and Theses (1997), Paper 3244
- [9] N. Abuaf, O.C. Jones Jr Optical probe for local void fraction and interface velocity measurements Review of Scientific Instruments 49, 1090 (1978); doi: 10.1063/1.1135524
- [10] L. Ong, J.R. Thome: Macro-to-microchannel transition in two-phase flow: Part 1 – Two-phase flow patterns and film thickness measurements, Experimental Thermal and Fluid Science 35 (2011) 37–47
- [11] C.L. Ong, J.R. Thome: Macro-to-microchannel transition in two-phase flow: Part 2 – Two-phase flow patterns and film thickness measurements, Experimental Thermal and Fluid Science 35 (2011) 873–886
- [12] C.M. Davis, E.F. Carome, et al.: Fiberoptic Sensors: technology handbook, Dynamic System Inc., (2000) Data Book III, Worverine Inc., Cap. 17
- [13] P. Carrica, V. Masson, P. Di Marco Application of a low-cost true-monofiber local phase detection probe to void fraction measurements in pool boiling, Proc. of 4th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, ExHFT 4, 1997, 293-300, Brussel, June 2-6