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SETUP AND FABRICATION OF COST EFFECTIVE, ROBUST FIBER OPTICAL NEEDLE PROBES FOR APPLICATION IN MULTIPHASE FLOWS

AUFBAU UND HERSTELLUNG VON KOSTENEFFIZIENTEN UND ROBUSTEN FASEROPTISCHEN SONDEN ZUM EINSATZ IN MEHRPHASENSTRÖMUNGEN

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Abstract

A fiber optical probe for detection of void fraction in multiphase flows consisting of silica fibers with core diameters of 200 and 400 µm is presented. Using beam splitter optics with a polarizing filter and a diode laser for illumination, a robust and cost-effective sensor was developed and evaluated in two phase flows with and without phase change. The setup and manufacturing process of the components as well as the post processing of the signals are described in detail.

Introduction

Fiber optical probes can be used for measuring a variety of physical parameters, including temperature, strain and vibrations. Fiber sensors are becoming more and more common due to their advantages like high physical robustness and insensitivity to electrical fields and high spatial and temporal resolution. A type of fiber sensor that has been commonly used in multiphase flows is the optical needle probe for determining void fraction and bubble size and/or velocity. This type of fiber optical sensors relies on the changes in refractive index at the tip of the fiber when a bubble passes the probe. For point measurements of void distribution in multiphase flows, fiber optical probes have been used by a number of authors over the last 40 years. An overview on the subject is given by Spindler and Hahne in Lehner et al. (1999), Cartellier und Achard (1991) and Delhaye in Kandlikar (1999). Detailed reviews of the technique were also given by Cartellier (1998), Vejrazka et al. (2010), Cartellier und Barrau (1998), Mena et al. (2008), Hong et al. (2004), and Juliá et al. (2005). Different types of probes have been proposed, of which the most common are the so called U-shaped fiber probe which consists mainly of a bent fiber with an emitter at one and a sensor at the other end and the monofiber probe where the light travels bidirectional in the fiber. Both types of probes detect different phases (gas/liquid) via the change in refractive index at the fiber tip and resulting changes in reflection of the beams according to Snellius' law (Lehner et al., 1999). With liquid present at the tip, the beam coming from the light source is emitted into the liquid, while with gas present total reflection occurs at the tip and light is reflected in the direction of the sensor. Using this effect, highly reliable time resolved point measurements of the void fraction can be achieved with minimum intrusiveness.

Probe setup, tip geometry

While the U-shaped fiber can be used with a less complex optical setup, the monofiber probe can have a smaller and more robust probe tip. As the setup of the tip was of high importance for the experiments discussed in this report, the monofiber setup was chosen. For all types of probes, the shape of the tips is of high importance. For the monofiber probe, the best tip-geometry in two-phase-flows is usually regarded to be a conical shape at a half cone angle between 43 and 51 degrees Cartellier und Achard (1991). For a simplified assumption of beams propagating parallel to the fiber axis, the three theoretical cases for the tip angles where the beam is reflected at both probe interfaces are shown in fig. 1. In reality, the criteria for reflection at the tip are more complex due to beams propagating at different angles in multimode fibers, so that changes in refractive index can also be measured with tips of smaller and larger angles. A more detailed discussion is given in Cartellier und Achard (1991). For the probes discussed here, a tip half-cone angle of 45° was chosen.

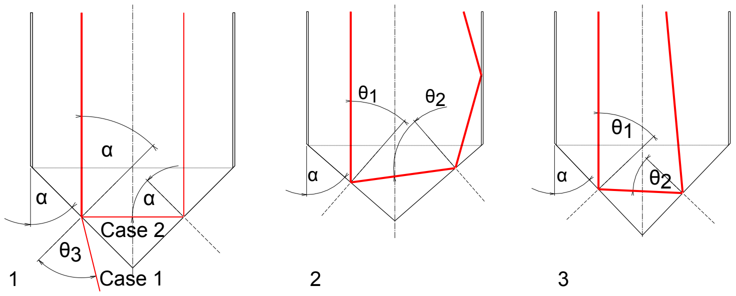

Fig. 1: (1) Tip-angle of 45 degrees, showing case 1 for transmission of light due to liquid and case 2 for total reflection due to gas at probe-tip; (2) maximum tip-angle (3) minimum tip-angle.

Separation of beams

For monofiber probes, two general setups used for separating the sending and transmitting beam have been proposed in literature. Firstly, the use of a beam splitter inserted between the fiber and the light source and secondly the use of a fiber coupler. For the probes presented here, the beam splitter setup was chosen as shown in fig. 2 because of the greater flexibility when using fibers with different diameters, the better access to the single beams and the lower costs for fibers with diameters greater than 100 µm.

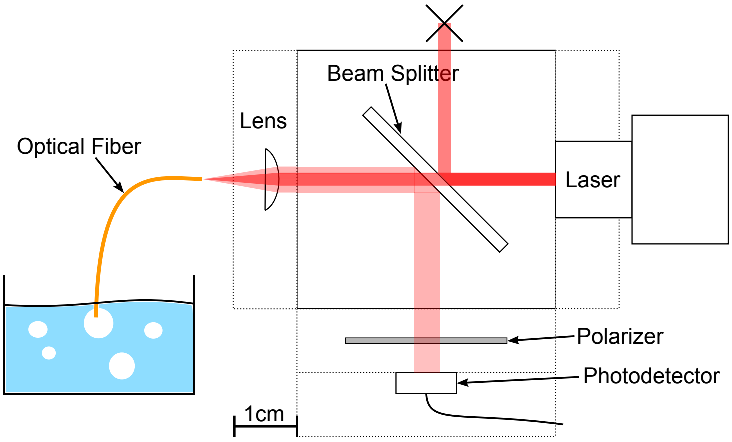

Fig. 2: Separation of beams for the optical probe.

Setup of the optical needle probe

The probe setup used in this report consisted of silica multimode fibers with a core diameter of $200\,\mu\mathrm{m}$ (Ratioplast-Optoelectronics HCS 200/230 µm) with a numerical aperture (NA) of 0.37. The fibers were illuminated with a diode-laser (Global Laser 1250 CW Cameo) with a wavelength of 650 nm and an output power of 1 mW. The beams were collimated into and out of the fiber via a plano-convex lens with a focal length of 5 mm. The sending and the reflected beam were separated via a beam splitter with a transmission/reflection ratio of 50:50. The intensity of the reflected beam was measured with a silicon photodiode (Siemens BPX 61) with a switching time of 20 ns attached to a signal amplifier and a data acquisition system. Parasitic reflections at the lens and at the end of the fiber were reduced using a polarizing filter that was inserted in front of the photodiode. As the light from the laser is linearly polarized, the unwanted reflections are also linearly polarized, while the light travelling through the fiber loses its polarization as the fibers used are not polarization maintaining. Thus, the unwanted reflection could be removed using the polarization filter. In this setup, the use of the polarizing filter led to an increase in difference in signal strength of approx. 100%. The optical setup was realized using the Qioptiq/Linos Microbench system as shown in fig. 4. In the experiments presented in this report,

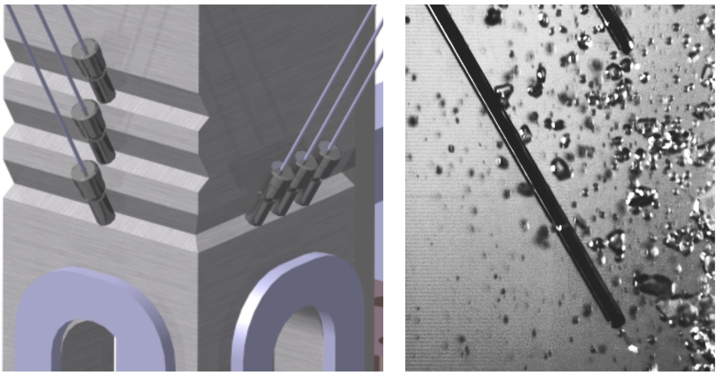

Fig. 3: Mounting of the probes in the channel used for boiling experiments: (left) CAD-drawing of channel with axially moveable mounted probes, (right) image of 2 probes in boiling flow.

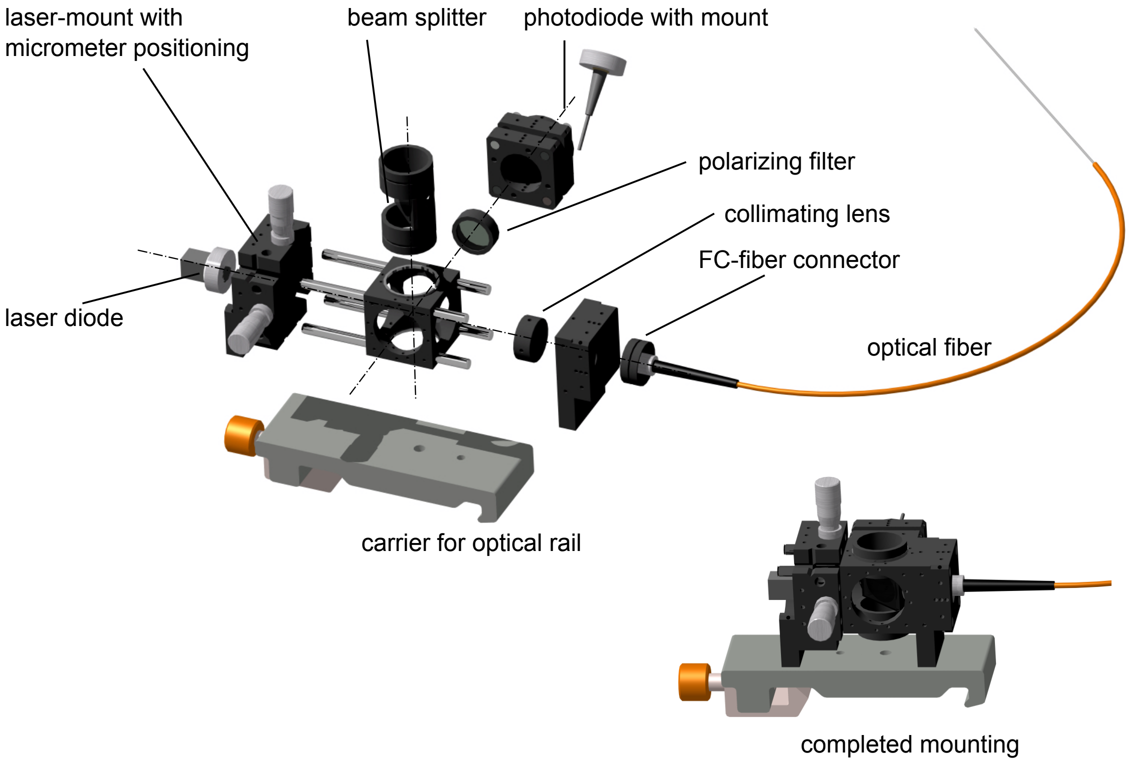

Fig. 4: Exploded and assembly drawing of the optical setup for beam separation and detection.

the data acquisition was run at frequencies of up to 3 kHz, however higher frequencies of up to 1 MHz were also feasible with the system. To ensure mechanical stability, the fibers were mounted in stainless steel tubes with an outer diameter of 1.4 mm. The probes were mounted axially moveable into the test channel using 1/16 in vacuum fittings with o-ring sealings (Swagelok SS-1-UT-A-4). The mounting of the probes is shown in fig. 3. Like this, the probes could be moved steplessly along the channel axis.

Fabrication of the fiber tip

One of the important points in the construction of optical needle probes is the fabrication of the tip of the fiber. For an ideal performance, the tip should have an angle of 45 degrees with a conical shape. At fiber diameters in the range of only few hundred micrometers, the fabrication of such a tip poses a challenge. Several ways of creating such tips have been discussed in recent literature. A commonly used technique is the etching of the tip with hydrofluoric acid (Cartellier (1998), Cartellier und Barrau (1998), Buchholz et al. (2004), Buchholz et al. (2006)). This technique can provide well shaped tips at a high reproducibility. Also, fibers with very small diameters can be used. For example, Buchholz et al. (2006) used a 8 µm fiber with a tip that was etched to less than 1.5 $\mu\mathrm{m}$. However, the technique requires an advanced setup for the etching process as well as the necessary safety measures for working with hydrofluoric acid. For the experiments reported here, fibers with diameters in the range of 200-400 $\mu\mathrm{m}$ were sufficiently small and mechanical stability was given priority over further miniaturization. Such, a simpler approach for the fabrication of the tips could be chosen. Instead of etching, the fibers were polished using a 0.3 micron lapping film (3M 268X) attached to a rotating disc and a micrometer stage to keep the fibers in position. The fibers were mounted in a capillary tube that allowed for rotation and thus enable conical shaping. The setup used for the polishing process is shown in fig. 5. Other angles and non-conical designs were also manufactured and tested but showed less clear results. With this technique, fibers with minimum diameters of down to 200 µm could be polished at a high rate of reproducibility. Fig. 6 shows 3 tips of fibers fabricated with this setup. The setup is economical, easy to use and requires no dangerous chemicals. However, fibers with diameters smaller than 200 µm proved to be difficult to handle.

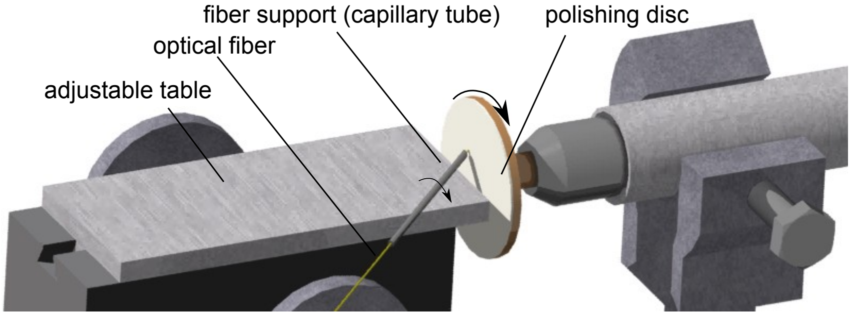

Fig. 5: Setup used for polishing of the fiber tips.

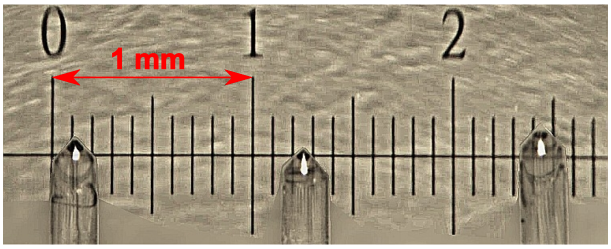

Fig. 6: Microscope image of 3 tips of the 200 micron fibers.

Signal treatment

The signals received from the photodiode were amplified to a range of 0-10 V. With the used setup, only little background noise was observed. Fig. 7 shows the received signal for two bubbles of different sizes in a boiling flow. The upper side of fig. 7 shows the raw voltage signal, and the lower hand shows the binarized signal used for further processing below. The signals were binarized using a phase indicator function (PIF) as described by Buchholz et al. (2004) (see eq. 1).

$$PIF(\vec{x},t) = \begin{cases} 1 & \text{for} \quad U \geq U_t \quad \text{(vapor)} \\ 0 & \text{for} \quad U \leq U_t \quad \text{(liquid)} \end{cases} \tag{1}$$

with PIF: Phase indicator function [-]
U: analogue voltage signal [V]
U_t: threshold voltage [V]

The threshold voltage U_t was defined as 2 Volts above the highest fluctuations of the basic noise measured for the probe in single phase liquid. Thus, a safe determination of vapor could

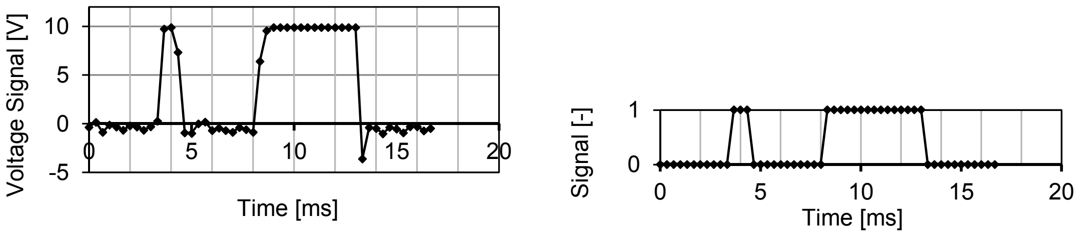

Fig. 7: Voltage signal and binarized signal for two detected bubbles of different sizes.

be achieved.

Using the binarized signals, the following parameters could be deduced:

- mean gas holdup by using a moving average function over a given time
- size distribution of vapor bubbles via contact time
- frequency of bubbles using FFT

Validation

To validate the reliability and accuracy of the probes, they were evaluated using both water and a low boiling liquid (3M Novec 649). Both showed clear signals, both for air and steam bubbles. To give informations about the influence on the flow, synchronous measurements with the optical probes and a high speed video camera were conducted. The probes showed only little influence on the bubble structure as can be seen in fig. 8 for a Taylor bubble of air in water penetrated with a 400 µm-probe and for smaller steam bubbles (Novec 649) and a 200 µm-probe in fig. 9 for a boiling flow. Fig. 9 also shows a comparison of the received signals from the probes with a videometric analysis of the of the contact time, which were in very good

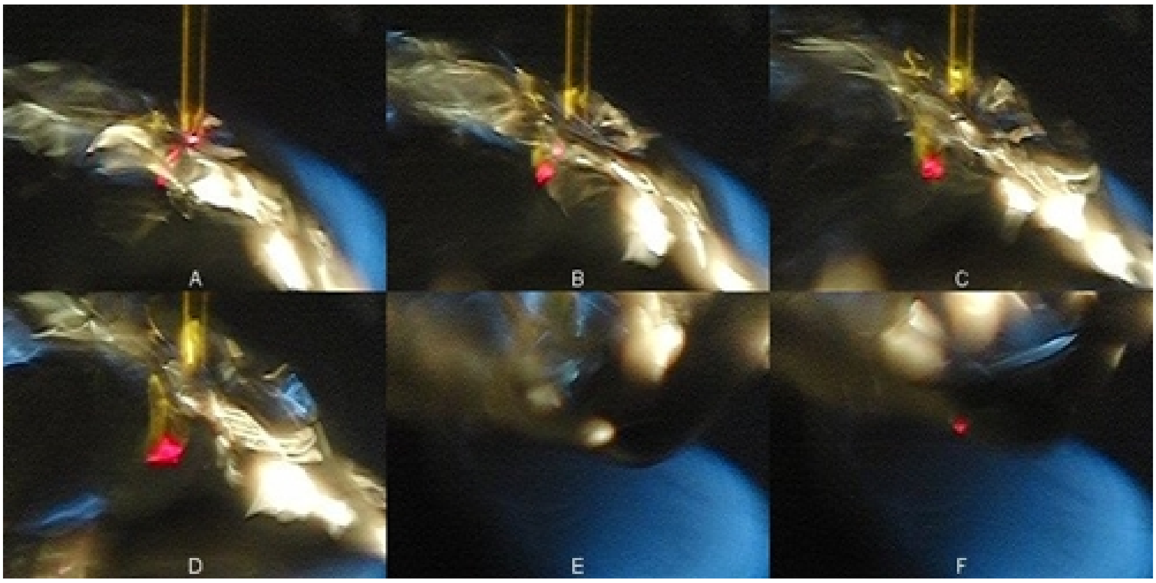

Fig. 8: A 400 µm probe penetrating an air bubble in water.

agreement. The probe angle was also varied in the validation experiments, but showed no influence on the results. To give an idea of the detectable bubble sizes, videometric images were compared to the measured signals from the probes. As a general approximation, a clear detection of the bubbles was possible for bubble sizes above ≈ 1.5 of the core-diameter of the sensing tip. This was in accordance with the results given by Vince et al. (1982), who reported a minimum detectable diameter of 1.66 times the core diameter. The probes were used in a large number of experiments and showed no defects even after more than 500 hours of operation, proving a good mechanical stability of the system.

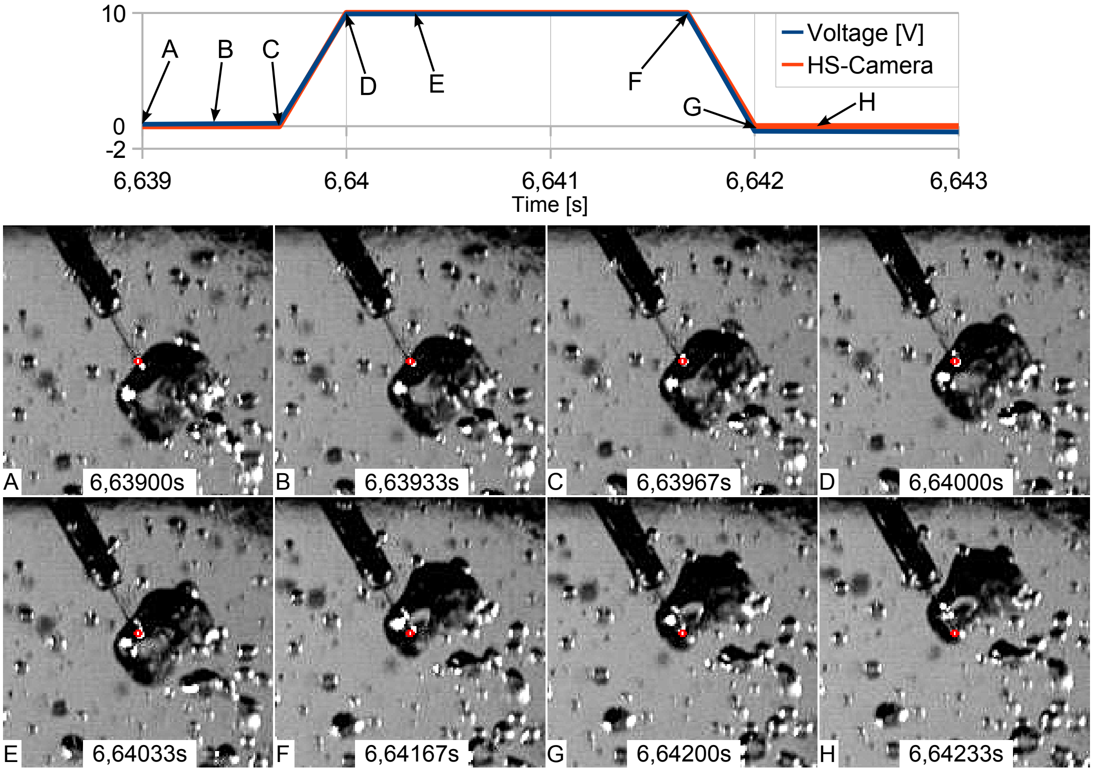

Fig. 9: Comparison of synchronous measurements by data acquisition module and high speed camera.

Summary and outlook

A measurement system using optical fibers for void detection in multiphase flows was designed and built. The setup of the measuring equipment as well as the fabrication steps for the fiber tip were thoroughly described. By adding a polarizing filter to the setup, the signal quality could be enhanced significantly. The shown setup offers a medium prized sensor capable of time resolved point measurements. Unlike electrical needle-probes, the optical probe can also be used in non-conducting media such as organic liquids and is practically immune to corrosion. The presented system could be used for detection of gas bubbles with a minimum diameter of 300 µm. For future works the system shall be used to measure gas holdup, bubble size distributions and frequencies in boiling experiments with low boiling liquids.

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