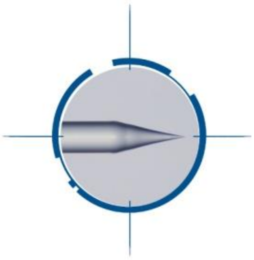
POP – an innovative Phase Detection Optical Probe for bubbly flows and sprays

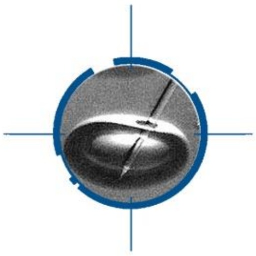
A2 Photonic Sensors’ *POP* is a family of advanced measurement devices using a unique technology based on over 25 years of research. It is dedicated to gas-liquid flow characterization and provides high-accuracy measurements of:

- Local concentration (void or liquid fraction)
- Inclusion (bubble or droplet) velocity
- Inclusion size (chord length)



From these measurements, the following physical quantities and functions can be determined:

- Chord and velocity distributions,
- Chord-velocity correlation,
- Flux and local flow rate.



Under assumptions about inclusion shape, *POP* can also compute the mean Sauter diameter d_{32}.

A2 Photonic Sensors’ *POP* can work for all kinds of gas-liquid flows, from bubbly flows to sprays and is especially suited for dense environments.

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Contents

System description and general set-up

The *POP* instrument is composed of the following parts:

- A micro-machined optical probe, to be immersed in the flow,
- An optoelectronic module, which can be remotely located,
- An acquisition and processing software.

The probe is linked to the optoelectronic module by several meters of optical fiber and the optoelectronic module is easily connected to a personal computer by a USB cable.

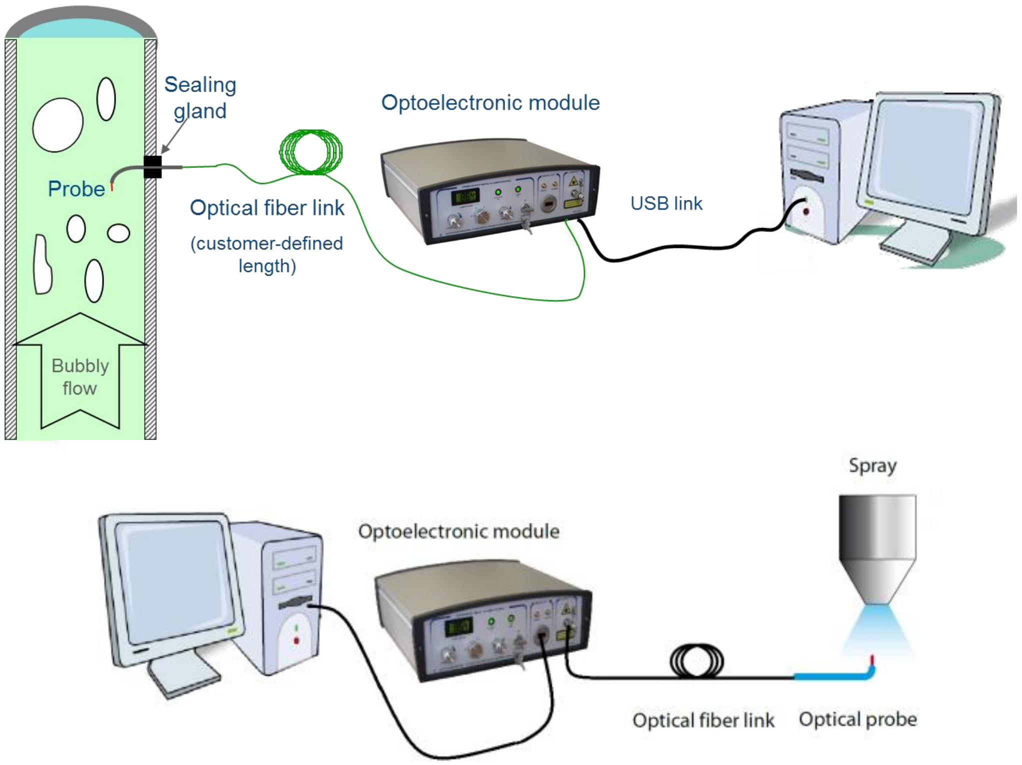

Figure 1 - System description and layout for bubbly flows (top) and sprays (bottom)

The probe itself is composed of an optical fiber held by a stainless steel tube. The end of the fiber is micro-machined in order to obtain a very thin and sharp tip. The sensing part of the sensor is only the end of the tip (typically the first 50 micrometers).

Figure 2 - A probe (left) and its sensing part (right)

The probe has to be immersed in the flow and will pierce all inclusions that reach its tip. For accurate measurement of velocities and chords, the probe has to be approximately parallel to the main flow direction (±15° or ±35° under certain conditions) at the measurement point. For void fraction measurement in bubbly flows, the probe can be used either parallel or perpendicular to the flow direction[1] (Figure 3.a).

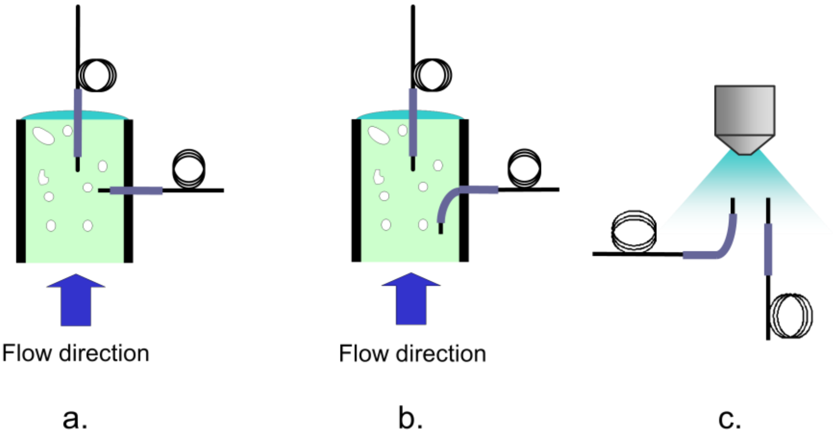

Figure 3 - Probe orientation for void fraction measurement in bubbly flow (a), velocity and chords in bubbly flows (b), and any measurement in sprays (c)

General working principle

Optical principle

The operation of A2 Photonic Sensors' *POP* relies on measuring the reflection of a laser beam at the interface between the probe tip and the surrounding phase. It is to be noted that the measurement principle does not require any light propagation outside the probe.

More precisely, a laser is emitted inside the probe, gets (partially) reflected at the probe tip, and bounces back toward the sensor.

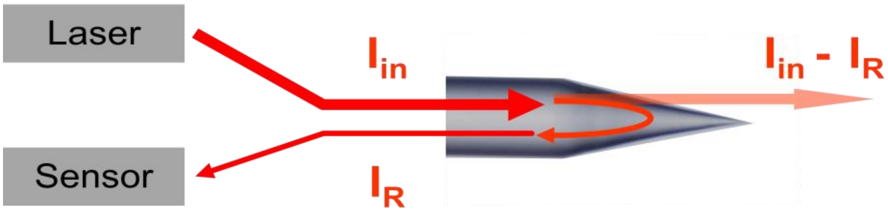

Figure 4 - reflection principle – the refracted light ($I_{in} – I_R$) is ignored

The sensor is sensitive to the refractive index of the phase surrounding its tip and measures a signal I_R close to the actual phase indicator function, i.e. the function defined to equal 1 in one phase, and 0 in the other. This knowledge about the phase changes enables to characterize the flow, as described hereafter.

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[1] Provided that the inclusion size has a greater order of magnitude than the probe itself, which is usually the case in bubbly flows.

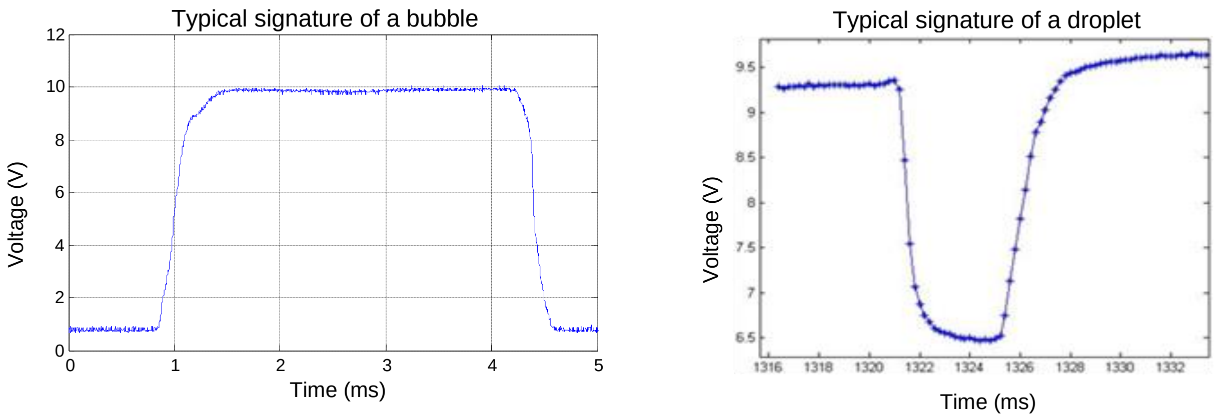

Figure 5 - Typical signals for inclusions

The probe has a sensing tip, whose length L_S is determined at manufacturing time. When the sensing tip is entirely immersed in one phase, the signal reaches the corresponding static level, high (for gas) or low (for liquid).

When an inclusion is pierced by the probe, the signal generated is a crenel where the first front corresponds to the moment when the probe starts piercing the inclusion and where the second front corresponds to the moment when the probe is exiting the inclusion. From this signal, the software extracts two durations: the signal rise time T_R and the crenel duration T_L, also called latency time or residence time.

Velocity measurement

The velocity measurement is based on the rise (or dewetting) time T_R, which is the time taken by the inclusion to propagate along the whole sensing tip of the probe.

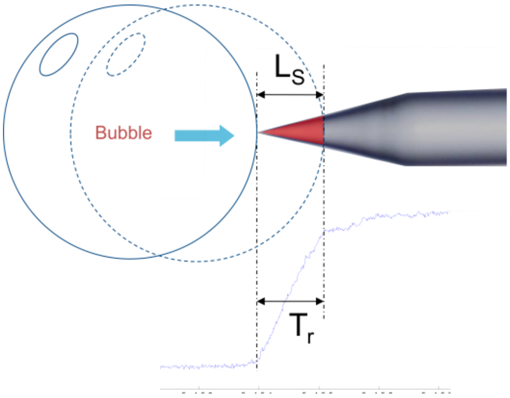

Figure 6 - Rise time measurement

Since the length of the sensing tip is known, the droplet velocity V_I can be computed with the formula:

$$V_I = \frac{L_S}{T_R}$$

Chord length measurement

The measurement of the chord length relies on the latency time T_{L}, corresponding to the time spent by the probe in the inclusion. From the velocity V_I computed as above, we can deduce the chord C_I of the observed inclusion:

$$C_I = T_L \times V_I$$

Of course, as illustrated by the figure below, the measured chord length is not always a diameter. But it is worth noting that this size measurement is independent from the inclusion shape.

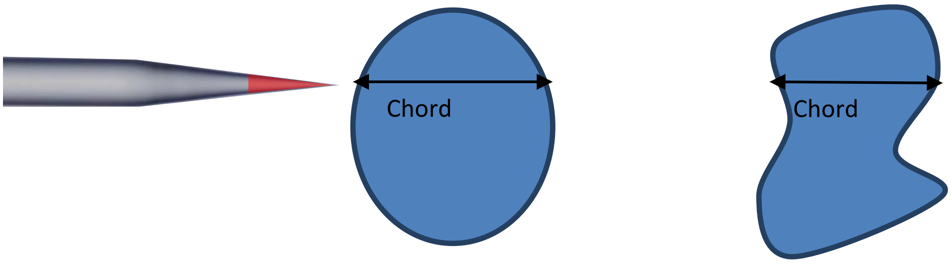

Figure 7 - Example of chords

Void or liquid fraction measurement

The latency time is also used directly to measure the void or liquid fraction of the flow. The void or liquid fraction is computed as the ratio of cumulated latency times observed by the probe to the total measurement time $\mathrm{T}_{\mathrm{Total}}$:

$$\alpha = \frac{\sum_i \mathrm{T}_{\mathrm{L_i}}}{\mathrm{T}_{\mathrm{Total}}}$$

Sauter diameter approximation

Once velocities are known, some post-processing operations are performed and enable the determination of other quantities, such as chord-velocity correlation and mean Sauter diameter (d_{32}). As shown by Liu and Clark[2], the mean Sauter diameter can be directly deduced from the mean chord using the relationship (valid for spherical and ellipsoidal inclusions):

$$d_{32} = \frac{3}{2} \times c_{10}$$

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[2] W. Liu and N.N. Clark, "Relationships between distributions of chord lengths and distributions of bubble sizes including their statistical parameters", Int. J. Multiphase Flow., 21 6, 1073-1089 (1995).

Key characteristics

- Mono-probe

  POP is a mono-probe system, which performs unambiguous measurement on a single location. As such, it is perfectly adapted to scattered flows.
- Little intrusive

  To our knowledge, *POP* is the narrowest probe ever, guaranteeing minimal disturbance on the flow.
- High frequency responsive

  POP is perfectly adapted to high-velocity flow characterization, as it provides an excellent frequency response.
- No limit on void fraction / hold-up

  POP is capable of working in very dense flows, which puts it one step ahead from image-based techniques for these environments.
- No transparency needed

  Thanks to its unique phase detection method, *POP* requires no transparency from the liquid phase.
- Industrial readiness

  POP is designed to fit industrial environments and severe conditions. In addition, the tiny size of the sensor itself and the fact that the measurement system can be remotely located are an asset when it comes to on-site measurements.
- Signal processing software

  POP measurement system includes signal processing algorithms that efficiently translate the physical phenomena into human-readable data. The raw, unprocessed data remain however available, if you wish to perform your own processing or to visually check the result consistency.

Performances

- Bubble diameter > 500 µm

  POP can work on bubbles as small as 100 µm, provided that the bubble velocity is high enough
- Droplet diameter > 10 µm
- No limit on the void fraction

  POP is suitable for very dense environments.
- No restriction on the inclusion shape
- Typical void or liquid fraction uncertainty ≈ 5 %
- Typical velocity and chord uncertainty ≈ 15 %
- Operating flow viscosity: up to 30x water viscosity
- Standard operating pressure and temperature: 30 bars / 80°C (maximum for custom systems: 100 bars, 200°C)
- No transparency required

  POP can work in opaque flow.

The main limitation of the *POP* system is that it is not adapted for turbulent flows, as the probe must be collinear to the inclusion trajectory (± 15°, up to ± 35° under certain conditions). A wetting issue may also appear with certain fluids, especially those of very high viscosity.

B-POP for bubbly flows and *S-POP* for sprays

Even though the same measurement principle applies to both bubbly flows and sprays, these environments have very different characteristics and call for specific measurement devices. Consequently, A2 Photonic Sensors manufactures *B-POP*, a family of specific *POP* systems for bubbly flows, and *S-POP*, specific *POP* systems for sprays:

- *Specific probes*: the manufacturing techniques take in particular into account the fact that the typical inclusion size is much smaller in sprays than in bubbly flows and that the velocity range is generally much higher.
- *Specific optoelectronic module*: the optoelectronic module used in sprays has to fulfil much higher requirements, as the mean velocity is usually much higher in such flows. The corresponding optoelectronic unit has therefore a better bandwidth and acquisition frequency.
- *Specific signal processing*: the signal processing software is dedicated to one kind of flow, because the physical wetting and dewetting phenomena are inverted, and because the sampling rates do not have the same order of magnitude.

Probe geometry

1C / 3C tip shapes for bubbly flows

For bubbly flows, A2 Photonic Sensors can provide 2 different geometries for *B-POP* probes: 1C and 3C.

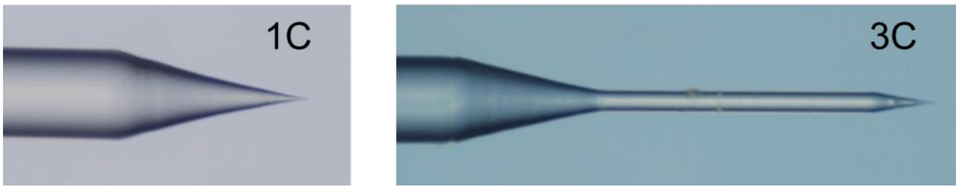


Figure 8 - 1C and 3C optical probe tip shape

The main difference between the two kinds is the length of the sensing part. Typically, the sensing length for 1C probes is $L_{1C} \approx 60$ µm, whereas 3C probes have a sensing length between 200 and 500 µm.

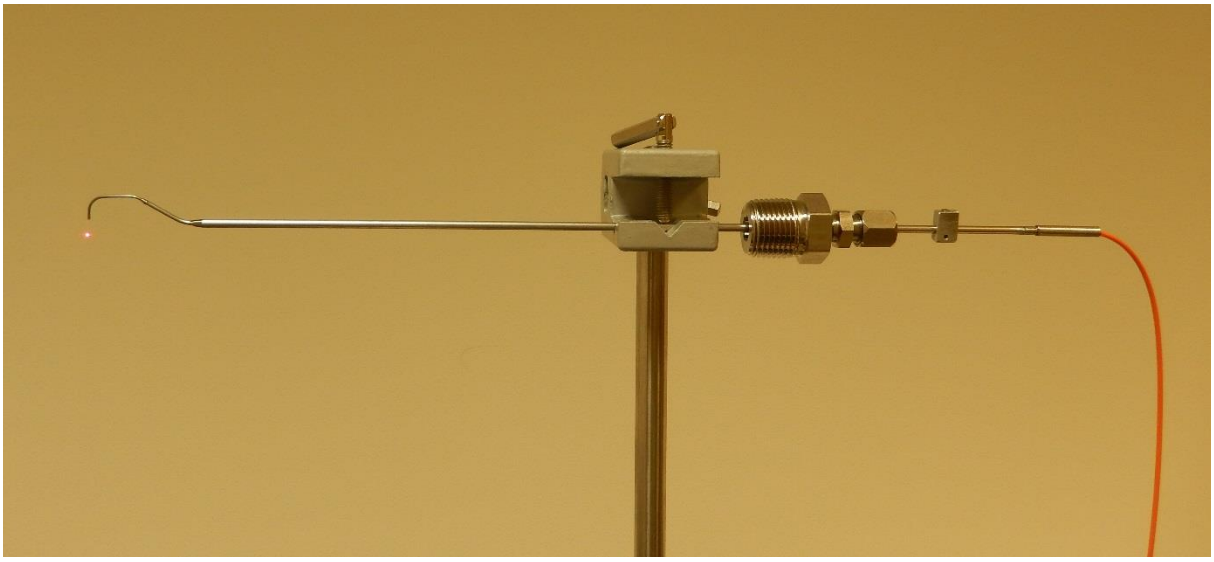
Thanks to their extended sensing length, 3C probes have a longer rise time T_R. As a consequence, the digitized signal has a better precision, and the measurement can be even more accurate. Alternatively, depending on your expectations in terms of accuracy, you may also safely reduce the digitizing sampling rate when using 3C probes.

3C probes are also less sensitive to the impact angle β and bring more tolerance on the flow direction (± 35° instead of ± 15° for 1C probes).

On the other hand, for tiny bubbles under 1mm in diameter, it is recommended to use the shorter 1C probes, which are more adapted to these conditions.

Geometry customization

All probes manufactured by A2 Photonic Sensors are designed individually, taking into account the characteristics of the experimental setup. Custom probe holders can also be designed and manufactured depending on your needs. In sprays, probes have most often a straight shape, while in bubbly columns, an L-shaped geometry is generally chosen. For certain cases, such as the traversal of a very thick wall, a special geometry called “micro-bent” can also be used.

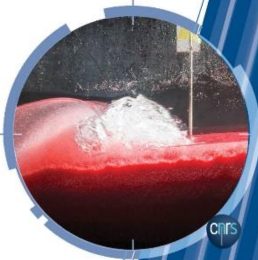


x-POP: some fields of application

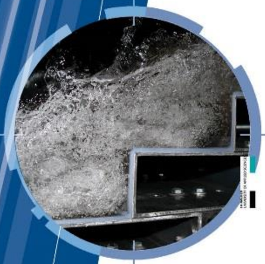
Spray nozzle for turbomachinery

Rain in climatic wind tunnel

High-pressure chemical reactor



Wave flume



Stepped spillway

Drilling fieldwork

Agricultural spraying

Optical Sensors
Innovative Solutions

Located at the foot of the French Alps, A2 Photonic Sensors designs and manufactures highly innovative micro probes, sensors and systems dedicated to liquid, gaseous and particle flow characterization.

As a spin-off of the LEGI and IMEP-LAHC laboratories, our offices are part of the Minatec campus, the centre for innovation in micro and nanotechnology in Grenoble, providing access to clean rooms and fluidic testbeds.

Our innovative approach to sensors is founded on the integration of miniature, high-performance optical elements, through the use of glass micro-technology. The benefits of our solutions include enhanced integration capabilities, extended measurement possibilities (dense environments, micro-metric measurements, micro-devices) and high flexibility on production volumes.

Contact us

八帆仪器设备（上海）有限公司
Eight-Sail Instrument & Equipment (Shanghai) Co., Ltd.
上海市 | 闵行区 | 新骏环路**189**号 | 漕河泾开发区创新创业园 | **C**座 **413**
室网址：**www.8sail.com**
电话：**021-31252000**
手机：**13524875604**
邮箱：**sales@8sail.com**