Measurement technique of bubble velocity and diameter in a bubble column via single-tip optical-fiber probing with judgment of the pierced position and angle

著者	Mizushima Yuki, Sakamoto Akihiro, Saito Takayuki
journal or publication title	Chemical Engineering Science
volume	100
page range	98-104
year	2013-08-30
出版者	Elsevier
権利	Copyright (C) 2013 Elsevier Ltd. All rights reserved.
URL	http://hdl.handle.net/10297/7388

doi: 10.1016/j.ces.2013.01.046

**Measurement technique of bubble velocity and diameter in a bubble column via
Single-Tip Optical-fiber Probing with judgment of the pierced position and angle**

Yuki Mizushima¹, Akihiro Sakamoto² and Takayuki Saito^{2*}

1) Graduate School of Engineering, Shizuoka University, 3-5-1 Johoku,

Naka-ku, Hamamatsu, Shizuoka 432-8561, Japan

2) Graduate School of Science and Technology, Shizuoka University, 3-5-1

Johoku, Naka-ku, Hamamatsu, Shizuoka 432-8561, Japan

*) Corresponding author, E-mail: ttsaito@ipc.shizuoka.ac.jp

Phone and Fax: +81 53 478 1601

ABSTRACT: Our objective is to improve the accuracy of bubble measurement with Single-Tip Optical fiber Probe (S-TOP) in a bubbly flow. The S-TOP measures a point-wise void fraction and a velocity and diameter of a bubble simultaneously, by using only a single

wedge-shaped tip. The S-TOP structure is very simple but raises an issue of an unclear touch position/angle between the S-TOP and a bubble. We propose a pre-signal threshold method in order to solve this issue. The pre-signal is one of the noisy optical signals from the S-TOP. First, the S-TOP signals are quantitatively analyzed with a newly developed 3D computational ray tracing method; the simulator can trace enormous ray segment trajectories in an optical fiber and render complicated optical boundary conditions. Moreover, in the simulator, evaluation of the complex output signals is achieved by computing the polarization and energy of every ray. We discovered that the intensity of the pre-signal indicates whether the S-TOP touches normally the center region of the bubble, or does not. We applied this characteristic to practical S-TOP measurement of a bubbly flow. As a result, the difference between the measured chord length via the S-TOP and the bubble minor axis from visualized images was significantly improved from 42 % (existing signal process) to 15 % (with processing through the method).

Keywords: Bubbly flow, Single-Tip Optical fiber Probe, Piercing positions, Measurement accuracy, Pre-signal, Computational ray tracing

1. INTRODUCTION

Bubbly flows appear in numerous industrial applications such as chemical industry, wastewater treatment, and environmental plant (e.g. Deckwer 1992; Krishna et al., 1997, 2000; Fan et al., 1999; Saito et al., 2000; Celata et al., 2006; Elena et al., 2011).

Gas-liquid mass transfer, one of the major interests of chemical engineers, is characterized by the overall volumetric mass transfer coefficient $k_L a$. The specific interfacial area, a , varies significantly with the hydrodynamic conditions.

Various physical or chemical methods have been applied to measure the specific interfacial area in the multiphase flows (e.g. Akita, & Yoshida, 1974; Patel, Daly, & Bukur, 1990; Luewisutthichat, Tsutsumi, & Yoshida, 1997; Pohorecki, Moniuk, & Zdrojkowski, 1999; Wu, & Ishii, 1999; Kulkarni et al., 2001; Kiambi et al., 2001; Hibiki, & Ishii, 2002). According to the descriptions in these papers, the interfacial area is given from the void fraction, bubble velocity and bubble size distribution. However, a

large number of the papers suffer from the bubble measurements, due to the extreme complexity of the bubbly flows. In addition, recently multiphase-reactor design based on computational fluid dynamics requires more information on the local flow characteristics, particularly the bubble properties, for physical models. To overcome this disparity, an Optical Fiber Probe (OFP) is one of the hopeful options. The OFP simultaneously measures diameters and velocities of the bubbles as well as the point-wise void fraction of the gas phase based on the residential time of every bubble pierced by the probe. Miller and Mitchie firstly reported the principle of the OFP method; they showed that Snell's law is applied to measuring bubbles (Miller and Mitchie 1969). Cartellier established a basis of the method to measure velocities and sizes of the bubbles and local void fractions by using a monofiber optical probe (Cartellier et al. 1992). Mudde and Saito reported that the flow regimes were described as the functions of the superficial gas velocity and geometrical property of bubble columns by using OFP and Laser Doppler Anemometry (LDA) (Mudde and Saito, 2001). Higuchi and Saito characterized long-period fluctuations in a bubble column, from point-wise time-series void fractions by using an OFP (Higuchi and Saito, 2010).

Many literatures raised issues of applying the OFP methods to the bubbly flows.

One of the issues is chord length measurement. A chord length measured through the probe depends on pierced conditions: a pierced position, and an angle between the bubble velocity vector and the OFP. Providing that an ellipsoidal bubble is measured through the probe, the probe piercing an edge of the bubble decreases pierced time (i.e. residential time); the probe piercing the center of the bubble increases the time. We have to know where and how the OFP has touched on the bubbles. Although Clark and his group developed a statistical way (Clark et al. 1996) in order to solve this problem, a difficult uncertainty remains. The theoretical study on the optic-signal is unsatisfied. In order to characterize the local hydrodynamics in a bubble column more deeply and accurately, we utilize informative optic-signals from the OFP.

In the present study, we propose a signal-centric analysis based on experiments and computations. At first, we conducted computational ray tracing (Sakamoto and Saito 2012) in a Single-Tip Optical fiber Probe (S-TOP, Saito et al. 2010). The ray tracing is a technique to trace paths and intensity of light and simulate the effects of its encounters with objects. By using this, we can numerically simulated optical effects in the S-TOP measurement, such as reflection, refraction, scattering, and dispersion phenomena. The characteristics of a pre-signal, which is one of the noise-like-signals, were clarified.

Second, we establish a discrimination method for piercing position/angle between the S-TOP and the bubble (Mizushima and Saito 2012). Finally, we discuss an accuracy of the S-TOP measurement in the bubbly flow.

2. MEASUREMENT PRINCIPLE OF SINGLE-TIP OPTICAL FIBER PROBE

2.1 Details of a Single-Tip Optical fiber Probe.

The schematic of the S-TOP employed in this study is shown in Fig. 1. The S-TOP is made from an optical fiber (synthetic quartz; step index type; the core diameter: 190 μm ; the clad thickness: 5 μm). The sensing tip is smoothly ground into a wedge shape. The fiber is fixed in a stainless capillary and a stainless tube.

The optical system used in the S-TOP measurement is illustrated in Fig. 2. A Laser diode (1) (wavelength 635 nm) is used for the light source of the S-TOP. The laser beams pass through a beam splitter (2) and are focused by an objective lens (3). The focused laser beams enter an optical fiber, and reach the S-TOP sensing tip (4). The laser beams reaching the tip surface are reflected/emitted at/from the tip. The return beams enter a photomultiplier (6) through a polarizer (5). Hence, we obtain ON/OFF

signals outputted from the photomultiplier. In succession, we analyzed the raw signals, and simultaneously obtained the velocities, diameters and number density of the bubbles. This method is valid for a gas hold-up (void fraction) up to about 20 % (Sakamoto and Saito, 2012). The upper limit of liquid-phase superficial velocity depends on the probe-tip diameter and the response speed of the optical detector; for instance, it is 10 to 15 m/s when 200 μm in tip diameter and an ordinary-type photo multiplier (e.g. RC200, Hamamatsu Photonics) are employed.

Figure 1. Structure of the S-TOP.

Figure 2. Optical system of the S-TOP.

2.2 Output signals delivered from the Single-Tip Optical fiber Probe.

Signals of the S-TOP from experiment and computation are shown in Figs. 3. Both signals are obtained from single bubble detection. The optical properties responsible for

the ON/OFF signal are reflection/refraction of light confined in the fiber. The computational ray tracing satisfactorily simulates this effect (Sakamoto and Saito 2012). Here, the light is modeled as thousands of very narrow beams, namely, rays. Reaching at the sensing tip, the rays are reflected or emitted, depending on the refractive indices of the mediums (gas: 1.00, water: 1.33) surrounding the tip (fiber-core: 1.44) and the angles of incidence/refraction of the rays. According to the Fresnel equations, which describe reflection/refraction of rays at an interface, we compute the signal as an intensity of return rays at inlet tip. At situation (1), the S-TOP tip is in the water: the rays reaching the tip emit into the water (Fig. 3(b)), i.e. the photo multiplier detects few return beams (the output remains the baseline-value). This results from the small difference in the refractive indices between fiber-core and water. At situation (2), the tip is covered with the bubble throughout: the beams are reflected back into the fiber and are promptly detected by the photo multiplier (the output becomes higher value). This results from the large difference in the refractive indices between fiber-core and gas. After the S-TOP penetrates the bubble rear surface, at situation (3), the tip is in the water again and the output returns to the baseline-value. The computational ray tracing clearly explain these behavior of the rays.

Before situation (2), the gas phase gradually covers the S-TOP tip, namely the output value gradually increases corresponding to the surface velocity; hence, the bubble velocity is calculated as follows. First, V_{Gas} (gas-phase output level) and V_{Liquid} (liquid-phase output level) are obtained using the histogram-method (Sakamoto and Saito 2010). Second, we obtain g_{rd} as the line of intersection of P_1 and P_2 from Fig. 3 and Eq. (1),

$$g_{rd} = \left(\frac{dV}{dt} \right) \frac{1}{(V_{Gas} - V_{Liquid})} . \quad (1)$$

Finally, U_b (bubble velocity) is calculated from g_{rd} and α (coefficient of proportionality) from Eq. (2),

$$U_b = \alpha \cdot g_{rd} . \quad (2)$$

Furthermore, the pierced chord length is calculated from Eq. (3), where $(t_e - t_s)$ is the residence time of the S-TOP tip covered completely with the bubble. The event time, t_s

(start time of S-TOP tip touching the bubble frontal surface) and t_e (end time of S-TOP tip slipping out of the bubble at the bubble rear surface), is detected by using the thresholds, V_{Liquid} and V_{Gas} ,

$$L_b = U_b \cdot (t_e - t_s). \quad (3)$$

Figure 3. S-TOP signal and corresponding images in the single bubble detection.

- (a) Typical output signal in a single bubble measurement.
- (b) Computational result of a single bubble measurement.

3. BASIS OF THE PRE-SIGNAL

3.1 Pre-signal.

One noise-like-peak is observed in Figs. 3 “A”, just before the S-TOP penetrates the bubble. We call this “pre-signal”. By using the computation, we track the history of the rays contributing to the pre-signal (Fig. 4). In Fig. 4, the optical signal is sorted according to the reflection surface, reflection at the tip and bubble-surface.

Basically, the pre-signal is caused by the reflection at the bubble-surface. First, the discharged rays from the S-TOP sensing tip are reflected at the bubble surface and re-enter the tip. In the meantime, the output voltage increases (Fig. 4 (a)). Second, touching the bubble frontal surface, the S-TOP starts to pierce the interface. The interface is deformed and a hollow is formed at the surface due to the surface tension. Most of the discharged beams are scattered at the hollow interface, and the amount of the re-entered rays into the S-TOP decrease. As a result, a steep fall of the pre-signal occurs (Fig. 4 (b)). Finally, the tip is exposed to the gas phase, and the amount of the reflection at the tip increases; hence, the output voltage increases (Fig. 4 (c)).

In particular, the pre-signal amplitude correlates with two parameters as illustrated in Fig. 5; a touch position of the S-TOP (non-dimensional touch position L/L_m), and an angle between the S-TOP axis and the bubble minor axis (touch angle θ). The reason for these definitions is that the rays from the S-TOP in water have directional characteristics (the rays are almost perpendicular with the S-TOP axis). Naturally, the gas-liquid interface should be normal to the S-TOP, in order to collect the surface reflection effectively. Hence, the desirable touch condition for detecting the intensive pre-signal is “ $L/L_m=0$ % and $\theta=0$ degrees”.

Figure 4. A simulated result via the S-TOP piercing a gas-liquid interface from water to air.

Figure 5. Parameters for the analysis of a two-dimensional S-TOP/interface interaction.

We also confirm the dependency on those parameters empirically. In this study, intensity level of the pre-signal V_P is defined as

$$V_P = (V_{Pmax} - V_{Liquid}) / (V_{Gas} - V_{Liquid}). \quad (4)$$

V_P at respective touch positions are plotted in Fig. 6 (a). V_P took the maximum, when the S-TOP touched at $L/L_m = 0$ %. V_P against the touch positions at $\theta = 15$ -45 degrees are plotted in Fig. 6 (b)-(d). Under these conditions, V_P depended on the touch

position/angle of the S-TOP. In fact, the touch condition at which V_P took the highest value was “ $L/L_m=0\%$ and $\theta=0$ degrees”.

Figure 6. The dependency of the pre-signal amplitude on the touch positions/angles.

- (a) Shift of V_P (The S-TOP is fixed normally).
- (b) Shift of V_P (The S-TOP is inclined by 15 degrees).
- (c) Shift of V_P (The S-TOP is inclined by 30 degrees).
- (d) Shift of V_P (The S-TOP is inclined by 45 degrees).

3.2 Pre-signal threshold method.

The S-TOP enables researchers to measure a bubble diameter and velocity and a local void fraction simultaneously. The issue, however, in a practical measurement via the S-TOP is that a touched position/angle on the bubble is unclear. It causes random errors and declines in the measurement accuracy. We therefore need to detect the position/angle pierced by the S-TOP, which is one of the major bottle-necks of the

optical fiber probe method. To overcome this problem, the pre-signal is very useful. Based on its characteristics, we rationally detect the touch position/angle of the S-TOP, from the pre-signal intensity level; i.e. the S-TOP touches normally the center region of a bubble, or does not. The amplitude of the pre-signal becomes the largest, only when the S-TOP pierces a bubble normally and at its center region. Hence, applying this particular characteristic, the touch position/angle can be detected (Mizushima and Saito 2012).

The algorithm is shown in Fig. 7. First, the raw data delivered from the S-TOP is obtained. Second, we scanned the data for the pre-signal of which intensity level is larger than the threshold ($V_p > 0.15$ as shown in Figs. 6), and then picked them up (effective in the pre-signal method, in Fig. 7). Finally, we obtained U_b and L_b from the extracted signals by Eqs. (2) and (3) (processed result). We call this a pre-signal threshold method. This sequence means that we deal with only the signals delivered at the perfect piercing condition (the S-TOP touched the bubble at its center, normally). Existing method calculates all of the raw data (not effective in the pre-signal method, in Fig. 7). In this way, calculated properties of bubbles have a lot of uncertainties

(unprocessed result). We demonstrate the effectiveness of the pre-signal threshold method empirically by comparing the processed/unprocessed results.

Figure 7. Algorithm of the pre-signal threshold method.

4. EXPERIMENTS

The experimental setup employed in this study is depicted in Fig. 8. A vessel made of an acrylic pipe (149 mm in inner diameter and 600 mm in height) was filled with degassed tap water. The vessel was covered with a rectangular acrylic water jacket to remove refraction and deformation in captured images. Bubble swarms were grown and launched from hypodermic needles (0.40 mm in inner diameter); using a bubble launch device that formed uniform bubbles at controllable launch timing. This device consists of a function generator, audio speakers, and two pressure controllers. A high-speed video camera visualized the bubbles. The parameters are shown in Table 1. The captured images were used as a reference data. The S-TOP was placed above the needles.

Thus, we made the uniform bubbles touch the S-TOP with arbitrary conditions (one bubble touches like hooked, another bounces, and so on). Through the pre-signal threshold method, we successfully extract the signals delivered at the perfect piercing condition.

Figure 8. The experimental setup for the bubble measurement.

Table 1. Bubble parameters in the bubble column experiments.

5. RESULTS AND DISCUSSIONS

5.1 Comparison of the results, visualization and S-TOP (unprocessed/processed).

The measurement results are shown in Fig. 9. These figures elucidate the effectiveness of the pre-signal method. The white bar indicates P.D.F obtained from the visualization, the dotted line is that from the S-TOP (unprocessed by the pre-signal method). The solid line represents the results from the S-TOP (processed by the pre-signal method). Each average value of the results is summarized in Table 1. In Fig.

9 (a), the velocity measurement results, the P.D.F of the visualization takes a peak only at 300 mm/s, while that of the S-TOP (unprocessed) is broad. The average velocity from the visualization is 295 mm/s, while that of the S-TOP (unprocessed) is 258 mm/s. The difference in the average velocities is about 13 %. These are caused by counting signals of incomplete piercing of the S-TOP; i.e. the S-TOP touches the edge area of the bubbles and the S-TOP scratches the bubbles. It is very difficult to distinguish the situation of the S-TOP touching a bubble; hence, usual signal processing cannot eliminate the unpleasant signals. As a result, the values of the S-TOP (unprocessed) have a widespread distribution. On the other hand, the P.D.F of the S-TOP (processed) apparently peaks at 325 mm/s; hence, by using the pre-signal method, the degree of precision of the S-TOP is significantly improved. The average velocity is 319 mm/s, and the difference between visualization and S-TOP results is reduced to 8 %.

Fig. 9 (b) shows the differences between measured chord length (S-TOP, unprocessed/processed) and the length of the bubble minor axis (visualization). Each average value is listed in Table 2. The pre-signal method remarkably improved the accuracy of the chord length measurement, because the method successfully removed the needless signals. The difference in the results of the visualization and S-TOP was

decreased from 42% to 15 %. Above all, the standard deviation of the chord length measurement is significantly improved from 0.5 mm (unprocessed) to 0.2 mm (processed). The pre-signal method is not only simple but also powerful to obtain accurate results from S-TOP signals.

Figure 9. Comparison of the results, visualization and S-TOP (unprocessed/processed).

(a) The bubble velocity measurement results.

(b) The bubble chord length measurement results.

Table 2. The average values of the velocity measurements.

Table 3. The average values of the chord length measurements.

5.2 Accuracy of the chordlength measurement.

The difference in the results between L_b (chord length) by the S-TOP (processed with the pre-signal threshold method) and L_{minor} (length of the bubble minor axis) by visualization is underestimated by 15%. This is a random error.

The measurement accuracy of chord length was theoretically/experimentally discussed in terms of bubbles in a quiescent flow (Julia et al. 2005). However, in a bubbly flow, bubble motions during the piercing dominate the accuracy of bubble diameter measurement. Asymmetrical deformation was quantitatively discussed by Vejražka et al; a horizontal shrinking of a bubble is observed while touching the probe (Vejražka et al. 2010). Additionally, bubbles behave unexpectedly due to their zigzag/helix motion, which is touching the probe (Mizushima and Saito 2012). Consequently, although the pre-signal intensity appears to be large, the bubble motion might be undesirable (Fig. 10). Obviously, these motions contribute to underestimation of L_b .

The dynamic motions depend on each bubble. It is a major issue of optical fiber probing in a bubbly flow. To overcome it, we have to know the piercing conditions in more detail from S-TOP signals.

Figure 10. The bubbly flow measurement via the S-TOP, the corresponding 2D images (x-direction: first column, y-direction: second column). Although the pre-signal appears intensively, the bubble does not ascend normally. This also shortens the measured chord length.

5.3 Applicability of the pre-signal threshold method.

The present investigation was conducted in the mono-dispersed bubbly flow in order to clearly discuss the effects of our proposal, under the condition without randomness of bubble diameters. Hence, there are some limitations in applying the pre-signal threshold method to an actual bubbly flow. The application range in bubble size for this method is 0.8–5 [mm] (volume-equivalent diameter).

The lower limit means the penetration limit of the S-TOP into the bubble, which means that it is difficult to overcome the surface tension force of the bubble. In this case, the calculated velocity and chord length will have an uncertainty owing to deceleration by the intrusiveness of the probe (Vejražka et al. 2010).

The upper limit of 5 [mm] is due to the geometrical instability of the bubbles. Bubbles in motion are generally classified by their shape as spherical, oblate ellipsoidal and spherical/ellipsoidal cap. The actual shape depends on the relative magnitude of the relevant forces acting on the bubble (Bhaga and Weber 1981). Large bubbles considerably oscillate (geometrically unstable), since the inertia force is more dominant than surface tension. The pre-signal threshold method assumes that the target bubble keeps its shape geometric. Also, the bubble motion is also susceptible to liquid turbulence. The motion is preferably moderate in the bubbly flow (i.e. liquid-phase superficial velocity is nearly equal to the bubble terminal velocity, e.g. chemical plant for phenol production). These geometrical instabilities complicate the detection. Depending on the magnitude of those, the upper limit decreases.

At least, Bubbles with diameter of about 1–5 [mm] (volume-equivalent diameter) are suitable for conventional probe methods. In reality, the developed method provides good coverage of this range.

6. CONCLUSION

In this study, we proposed a signal-centric analysis based on the experiments and the numerical ray tracing method. The discrimination method to detect where and how the S-TOP has touched bubbles was developed. This method successfully overcame the S-TOP measurement problem, and remarkably improved the precision and accuracy of the S-TOP measurement with no-statistical process. The difference in the bubble minor axis measurement between visualization and the S-TOP decreases from -42% to -15 %. This method provides a simple yet powerful method for the optical fiber probing. We will find out a further potential hidden in the probe signals with both empirical and numerical way.

REFERENCES

- Akita, K., Yoshida, F., 1973. Gas holdup and volumetric mass transfer coefficient in bubble columns. Effect of liquid properties. *Ind. Eng. Chem. Proc. DD.*, 12, 76-80.
- Bhaga, D., Weber, M. E., 1981. Bubbles in viscous liquids: shapes, wakes and velocities. *J. Fluid Mech.*, 105, 61-85.
- Cartellier, A., 1992. Simultaneous void fraction measurement, bubble velocity, and size estimate using a single optical probe in gas-liquid two-phase flows. *Rev. Sci.*

Instrum., 63, 5442-5452.

Celata, G. P., Cumo, M., D'Annibale, F., Di Marco, P., Tomiyama, A., Zovini, C., 2006.

Effect of gas injection mode and purity of liquid on bubble rising in two-component systems. *Exp. Therm. Fluid Sci.*, 31, 37-53.

Clark, N. N., Liu, W., Turton, R., 1996. Data interpretation techniques for inferring bubble size distribution from probe signals in fluidized systems. *Powder Technol.*, 88, 179-188.

Deckwer, W. -D., 1992. *Bubble Column Reactors*. John Wiley & Sons, Chichester, England.

Elena, M. C., Díaz, M. E., Francisco J. M., Miguel, A. G., 2011. Unified study of flow regimes and gas holdup in the presence of positive and negative surfactants in a non-uniformly aerated bubble column. *Chem. Eng. Sci.*, 66, 4047-4058.

Fan, L. S., Yang, G. Q., Lee, D. J., Tsuchiya, K., Luo, X., 1999. Some aspects of high-pressure phenomena of bubbles in liquid and liquid–solid suspensions. *Chem. Eng. Sci.*, 54, 4681-4709.

Hibiki, T., Ishii, M., 2002. Interfacial Area Concentration of Bubbly Flow Systems. *Chem. Eng. Sci.*, 57, 3967-3977.

- Higuchi, M., Saito, T., 2010. Quantitative characterizations of long-period fluctuations in a large-diameter bubble column based on point-wise void fraction measurements. Chem. Eng. J., 160, 284-292.
- Juliá, J. E., Harteveld, W. K., Mudde, R. F., Van Den Akker, H. E. A., 2005. On the accuracy of the void fraction measurements using optical probes in bubbly flows. Rev. Sci. Instrum., 76, 035103.
- Kiambi, S. L., Duquenne, A. M., Bascoul, A., Delmas, H., 2001. Measurements of local interfacial area: application of bi-optical fiber technique. Chem. Eng. Sci., 56, 6447-6453.
- Krishna, R., De Swart, J. W. A., Ellenberger, J., Martina, G. B., Maretto, C., 1997. Gas holdup in slurry bubble columns: effect of column diameter and slurry concentrations A.I.Ch.E. J., 43, 311-316.
- Krishna, R., Sie, S. T., 2000. Design and scale-up of the Fischer-Tropsch bubble column slurry reactor. Fuel Process. Technol., 64, 73-105.
- Kulkarni, A. A., Joshi, J. B., Kumar, V. R., Kulkarni, B. D., 2001. Simultaneous measurement of holdup profiles and interfacial area using LDA in bubble columns:

- Predictions by multiresolution analysis and comparison with experiments. Chem. Eng. Sci., 56, 6437-6445.
- Luewisuthichat, W., Tsutsumi, A., Yoshida, K., 1996. Deterministic chaos analysis of particle dynamics in three-phase systems. Journal of Chemical Engineering of Japan, 29, 675-682.
- Luewisutthichat, W., Tsutsumi, A., Yoshida, K., 1997. Chaotic hydrodynamics of continuous single-bubble flow systems. Chem. Eng. Sci., 52, 3685-3691.
- Miller, N., Mitchie, R. E., 1970. Measurement of local voidage in liquid/gas two-phase flow systems. J. Brit. Nucl. Energy Soc., 2, 94-100.
- Mizushima, Y., Saito, T., 2012. Detection method of a position pierced by a single-tip optical fibre probe in bubble measurement. Measure. Sci. Technol., 23, 085308.
- Mudde, R. F., Saito, T., 2001. Hydrodynamical similarities between bubble column and bubbly pipe flow. J. Fluid. Mech., 437, 203-228.
- Patel, S. A., Daly, J. G., Bukur, D. B., 1990. Bubble-size distribution in Fischer Tropsch-derived waxes in a bubble column. A.I.Ch.E. J., 36, 93-105.
- Pohorecki, R., Moniuk, W., Zdrójkowski, A., 1999. Hydrodynamics of a bubble column under elevated pressure. Chem. Eng. Sci., 54, 5187-5193.

Saito, T., Kajishima, T., Nagaosa, R., 2000. CO₂ Sequestration at Sea by Gas-Lift System of Shallow Injection and Deep Releasing. *Environ. Sci. Technol.*, 34, 4140-4145.

Saito, T., Mudde, R. F., 2001. Performance of 4-tip optical fibre probe and bubble characterizations by the probe in turbulent bubbly flows. *Proc. Int. Conf. on Multiphase Flow 2001* Paper no. 111, in CD-ROM.

Saito, T., Matsuda, K., Ozawa, Y., Oishi, S., Aoshima, S., 2009. Measurement of tiny droplets using a newly developed optical fibre probe micro-fabricated by a femtosecond pulse laser. *Measure. Sci. Technol.*, 20, 114002.

Sakamoto, A., Saito, T., 2012. Robust algorithms for quantifying noisy signals of optical fiber probes employed in industrial-scale practical bubbly flows. *Int. J. Multiphase Flow*, 41, 77-90.

Sakamoto, A., Saito, T., 2012. Analysis of optical fiber probing based on a ray tracing. *Rev. Sci. Instrum.*, 83, 075107.

Vejražka, J., Večeř, M., Orvalho, S., Sechet, P., Ruzicka, M. C., Cartellier A., 2010. Measurement accuracy of a mono-fibre optical probe in a bubbly flow. *Int. J. Multiphase Flow*, 36, 533-548.

Wu, Q., Ishii, M., 1999. Sensitivity study on double-sensor conductivity probe for the measurement of interfacial area concentration in bubbly flow. *Int. J. Multiphase Flow*, 25, 155-173.

Figure 1. Structure of the S-TOP.

(1) Laser diode, (2) Beam splitter, (3) Objective lens, (4) S-TOP, (5) Polarizer, (6) Photo multiplier, (7) Amplifier, (8) Digital oscilloscope.

Figure 2. Optical system of the S-TOP.

(a) Typical output signal in a single bubble measurement.

(b) Computational result of a single bubble measurement.

Figure 3. S-TOP signal and corresponding images in the single bubble detection.

Figure 4. A simulated result via the S-TOP piercing a gas-liquid interface from water to air.

Figure 5. Parameters for the analysis of a two-dimensional S-TOP/interface interaction.

(a) Shift of V_p (The S-TOP is fixed vertically). (b) Shift of V_p (The S-TOP is inclined by 15 degrees). (c) Shift of V_p (The S-TOP is inclined by 30 degrees). (d) Shift of V_p (The S-TOP is inclined by 45 degrees).**Figure 6.** The dependency of the pre-signal³¹ amplitude on the touch positions/angles.

Figure 7. Algorithm of the pre-signal threshold method.

(a) Optics, (b) S-TOP, (c) Cylindrical vessel, (d) Rectangular water jacket, (e) Recorder, (f) Halogen light source, (g) Bubble launch device, (h) Needles, (i) High-speed video camera, (j) PC

Figure 8. The experimental setup for the bubble measurement.

(a) The bubble velocity measurement results.

(b) The bubble chord length measurement results.

Figure 9. Comparison of the results, visualization and S-TOP (unprocessed/processed).

Figure 10. The bubbly flow measurement via the S-TOP, the corresponding 2D images (x-direction: first column, y-direction: second column). Although the pre-signal appears intensively, the bubble does not ascend normally. This also shortens the measured chord length.

Table 1. Bubble parameters in the bubble column experiments.

Bubble ascending velocity	295 [mm/s]
Bubble aspect ratio	0.47 [-]
D_{eq}	2.64 [mm]
Re	770 [-]

Table 2. The average values of the velocity measurements.

	S-TOP	Visualization	difference
	[mm/s]	[mm/s]	[%]
unprocessed	258	295	-13
processed	319		8

Table 3. The average values of the chord length measurements.

	S-TOP	Visualization	difference
	[mm]	[mm]	[%]
unprocessed	0.93	1.59	-42
processed	1.25		-21