Characterization of bubble cloud quality and evolution using optical probes

J. Bouvard\textsuperscript{1}, C. Béguin\textsuperscript{1}, S. Etienne\textsuperscript{1}, D. Scott\textsuperscript{2}, L. Bornard\textsuperscript{2}

\textsuperscript{1} Polytechnique Montréal, Mechanical Engineering Dept, Canada.
\textsuperscript{2} Hydrodynamics Engineering, Hydro Solutions, GE Renewable Energy, Canada.
E-mail: stephane.etienne@polymtl.ca

Résumé. The mechanics of bubble clouds are essential to many industrial processes in the energy and chemical realms. In the specific case of hydroelectric turbines, bubble clouds are present when air is injected into the water to increase dissolved oxygen levels in the water flowing through the powerplant. Understanding the physics of the phenomena driving the mixing of bubbles is still needed to improve the modeling of such flows. Even in less complicated geometries such as those found in many laboratory flows, measurements of bubble cloud evolution are sparse and validation of numerical models is difficult. Descriptions of the evolution of bubble clouds in simple geometries are therefore required. These can then be used to predict the distribution in more complex geometries through correlation laws. The present work aims at fulfilling such needs. An experimental water loop is used in conjunction to cross-flow air injection to produce bubble clouds and test injection devices.

1. Introduction

In hydroelectric sites, the dissolved oxygen (DO) can reach alarmingly low level under some weather conditions, which endangers the aquatic life as such low concentration triggers the death of large amounts of fish if it remains for a few hours [1]. The chosen option by the industry to up the concentration of DO is the injection of oxygen inside the penstock pipe. The air injection in stagnant water was extensively researched, cf. the state of the art from Kumar and Kuloor [2], and lots of analytic models were developed [3, 4, 5]. However, these studies often focuses on a very limited number of bubbles, on the contrary of what is needed for the hydroelectric plants.

More recently, some studies were conducted to measure the evolution of the DO depending on the injector’s geometry [1, 6, 7]. But once again, the circular holes and porous media analyzed were used in still water. Some models and experiments were made in co-flowing configuration [3, 4, 8, 9], but only a handful in a cross-flow one [10, 11, 12]. Furthermore, these sparse studies fail to extensively document bubble clouds, bubble clouds which are the focus of the present work.

2. Experimental apparatus

The main experiments were conducted on a closed test loop of about ten meters long and one meter high. A 40 HP pump (i.e. 30 kW) enables the water flow to reach 40 L.s\textsuperscript{-1}. This loop includes a 45 cm long test vein (i.e. in the flow direction $x$), 20 cm high ($z$ direction) and 10 cm wide ($y$ direction), in which all measurements were made.

The goals of this set-up are the following:
To inject air in a controlled manner, i.e. with different water flows and different geometries for the injector, in the vein;
- To visualize the behavior of the air injected;
- To measure pressure at different locations in the vein;
- To measure the characteristics of the two-phase flow, i.e. void fraction, bubbles size and velocity.

2.1. Air injection

To get as close as possible to the actual conditions, i.e. the pipes of the hydroelectric plant, it is required that air injection be perpendicular to the flow. To fulfill these conditions, air is injected from orifice plates at the bottom of the vein. An air chamber between the air pipe and the plate serves as a buffer to avoid potential vibrations and to measure pressure.

The test section consists of 4 acrylic slabs 0.5 inches thick screwed to an Aluminum frame. The design of the lower slab was made to facilitate changing the geometry of the injector, as can be seen in Figure 1. On this lower surface, the top is 1 inch thick with a recess for the injection slabs so that it is easier to switch between various injector geometries. The impermeability of the vein is ensured by O-rings compressed by the outer slabs, e.g. the lower one, while the integrity of the air chamber is maintained by either the fusion of acrylic slabs with dichloromethane and some silicone, either the rubber seal (in blue in Figure 1), or an O-ring between the 1 inch and the interchangeable injection slabs. Apart from the 1 inch slab, all the others were manufactured with a laser cutter, then tapped manually if needed.

The lower plate was drilled and tapped in order to plug in a pipe connected to the compressed air system. A rotameter placed upstream, with a range from 0 to 8 SCFM, allows to control the air flow injected. As the main goal is to optimize air-water exchanges, and this is achieved with small bubbles, the injectors’ geometry aims towards small openings. To limit pressure drop, slots were preferred to circular holes of diameter equal to the width of the slot.

![Figure 1: Assembly of the injection system. The thin blue slab is the rubber seal, everything else is in acrylic including the green plate which is the interchangeable injection plate.](image)

2.2. Flow visualization

A fast camera, MotionBlitz Cube 4, is used in conjunction with powerful spot lights to get enough light in the vein for quality video capturing. Videos are taken with the Mikrotron MotionBlitz Cube software, then processed with ImageJ. While imaging allows to observe the periphery of two-phase flows, description of the flow cannot go deep insight bubble clouds. To this respect, two other measurement devices are used to explore the quality of bubble clouds: pressure (static pressure sensors and Pitot tubes) and optical probes.
2.3. Pressure measurements

To explore the effect of air injection on the pressure profile along the vein, pressure probes are used. To reach a sufficiently fine description of the flow pressure, five sensors were installed on one of the side windows of the vein. Three of these sensors record the static pressure, relative to atmospheric, while the two others are each plugged in a Pitot tube which determine dynamic pressure, and flow velocity. Another sensor is plugged in the air chamber. These pressure sensors, from the PX26 series of Omega, are plugged to a strain meter used to display the pressure and to amplify the output signal to make it usable into Labview.

2.4. Optical probe

Two-phase flows present several characteristics that are difficult to measure without being intrusive, e.g. void fraction $\varepsilon$, which is the ratio of the volume of gas to the total volume, the size and the speed of the bubbles. Fast camera imaging helps characterizing global two-phase flow quality, but it appears of little help when measuring void fractions.

Optical probes, while intrusive, give access to accurate measurements of bubble size, velocity and local void fraction. The principle of the probes we use is the following: two identical optical fibers whose ends are spatially shifted by about 0.1 mm (cf. Figure 2), can detect if they are inside an air or a water phase. Then, comparing the signals received while knowing precisely $\Delta h$, we can deduce bubble velocity and sizes. From this data, the local void fraction is determined.

![Figure 2: Diagram of the end of the optical probe. The distance $\Delta h$ between the two tips is usually 100-200 $\mu$m.](image)

The optical probe itself can only move in one direction, thanks to its micrometric screw, so it should be nested in a two-dimensional mobile system in order to be able to make measurements in the entire vein. A bidirectional Velmex system was chosen to fulfill this role. It steers the motion of a movable slab in which the probe is embedded, and which slides above the vein. Some parts of this device can be seen in Figure 3. The upper acrylic slab has been redesigned to include a large opening of 10 by 1 3/4 inches allowing the optical probe to make measurements in the bubble jet. An O-ring surrounding the opening guarantees the impermeability. To keep this system in place, four flat angle brackets were attached to the side windows of the vein. A system of strut channels and steel bars ensures the cohesion of the whole and allows the desired displacement of the probe.

2.5. Experimental limitations

- The water flow rate can go from 2.5 up to 40 L·s$^{-1}$;
- The air flow rate up to 15 SCFM, i.e. up to 30% of the liquid volumetric flow rate. This range of air to water volumetric flow rate ratio encompasses what is required in hydroelectric turbines in order to increase DO to an adequate level;
- The volume reachable for probe measurement is 6×1×2 inches;
- The bubble detection threshold is from 50 to 100 $\mu$m;
3. Results

3.1. Flow visualizations

Thanks to the high speed camera, some videos were made for various combinations of air and flow rates at a frequency of 1 kHz. Visualizations were also made for different geometries of the injector to try and compare their ability at creating various bubble clouds. The visual performances of the injectors, i.e., the capability to induce a flow where the air is divided into numerous small bubbles, were similar and only meticulous observations could find some differences. Note that it is difficult to extrapolate cloud quality from an external viewing.

3.2. Pressure measurements

Results of this section have been obtained for a different injector geometry than the one shown in Figure 1. The precise locations and denominations of each sensor is referenced in Figure 3.

3.2.1. Transient state

Pressure history shows that the flow rapidly becomes steady. In Figure 5, the experimental conditions were modified at 974 seconds. First, we increased the air flow, and a few seconds later the water flow. In 10 seconds the experimental conditions are changed, and less than 10 seconds later the pressures are stabilized. No large variations of pressure can be observed over time which reveals stability of the flow on average. Some things worth noting are, first, the increased dynamic pressure downstream when the air flow is significant, which is coherent as the air injected takes up some volume of the section and so, as the water flow rate is constant, the water velocity increases. The three static sensors measuring the pressure at different points in the vein are quite similar.

3.2.2. Pressure losses

To determine the effect of air and water flow rates on pressure losses and gains, i.e., the effect of water velocity and void fraction, measurements were made to map the range of our
set-up. For each measurement point 120 seconds were recorded, starting at least 90 seconds after the experimental parameters were adjusted to ensure that a steady state was established. The acquisition rate was of 2 kHz, so each that each pressure data acquisition was made of between 180 000 and 240 000 points. The differences in air flow when varying pressure losses are shown in Figure 6.

We can notice an increase of the volumetric air flow with an increase of the pressure losses $h = P_4 - P_2$ and $h_1 = P_1 - P_2$, both during the injection, respectively between the air chamber and the injection sensors, and between the first two static sensors in the vein. The first pressure loss $h$ (Figure 6, upper-left) was expected, and meaningful as the differential of pressure reaches nearly 50 kPa for the highest air flow. The experimental data can be fitted quite nicely with a cubic root as one can see. The multiplicative constant might be function of the geometry of the injector, so it might be one parameter allowing to access the performance of the injector. Furthermore, this cubic increase is not
characteristic of the diphasic flow, as it is still present without water in the vein (Figure 6, lower-left). Though, the expected fit would have been a square root as the pressure loss is usually proportional to the square of the flow velocity, thus to the square of the volumetric flow rate [13]:

\[ h = \frac{1}{2} K \rho v^2 \]  

(1)

with \( h \) the pressure loss, \( v \) the flow velocity, \( \rho \) the volumetric mass density of the fluid and \( K \) the loss coefficient. Nevertheless, the theoretical pressure drop due to the sudden contraction and expansion, calculated with the empirical coefficients from White [13], is of the right order of magnitude and accounts for approximately half of the pressure drops measured. The other half should come from the height of the slot.

The second pressure loss \( h_1 \) (Figure 6, upper-right) was not expected as an injection of air should have resulted in a gain of pressure instead of a loss. Nevertheless, the pressure differences are a lot smaller than the ones for the air injection. The pressure loss along the vein \( h_2 = P1 - P3 \), i.e. between the upstream sensor and the downstream one, shows also an interesting pattern which seems to be mainly dependent on the air flow, but not only (Figure 6, lower-right). Unlike the two other pressure losses presented in Figure 6, this one seems to have a small but noticeable influence from the water flow. This pressure drop
is of the same order as $h_1$, i.e. negligible compared to $h$, but it exhibits a different behavior. Besides the shift with the water velocity, which implies that both the water flow and the air flow are responsible of the pressure drop, the air flow seems linear with $h_2$.

### 3.2.3. Pitot tubes

The water velocity, as calculated from the dynamic pressures provided by the Pitot tubes, is displayed in Figure 7 as a function of the volumetric flow rate of water. As expected, the water velocity seen by the upstream Pitot before the air injection is not influenced by the volumetric quality $\beta$ and is linear with the volumetric flow rate of water (Figure 7, left)). The slope of this straight line gives us the inverse of the effective cross section $S$, as $D_{water} = SU_{water}$. We obtain $S = 1.8 \times 10^{-2}$ m$^2$, which is coherent with the experimental apparatus as we have a 200 cm$^2$ cross section obstructed by the injection system for about 30 cm$^2$. Considering the lack of honeycomb in the water tunnel, this error of about 6% can be explained by the non-uniformity of the upstream flow.

The downstream Pitot is witnessing the same velocity for low air injection, but, as the volumetric quality rises, the water velocity is gradually increasing as well for a volumetric flow rate of water $D_{water} > 10$ L$\cdot$s$^{-1}$ (Figure 7, right)). The fluids are considered incompressible in the vein, so the mass conservation implies the conservation of the volumetric flow rate inside the vein. So the more the air flow increases, the more the effective cross section of water decreases, and so the more the water velocity rises. We can also notice that there is an offset of 0.4 m$\cdot$s$^{-1}$ with the measures, an offset that can be explained by a vertical shift of 8 mm of water between the two extremities of the differential sensor.

![Figure 7](image-url)

**Figure 7:** Water velocity deduced from the dynamic pressures provided by the Pitot tubes, function of the volumetric flow rate of water. Graphs for the upstream Pitot (left), and the downstream one (right). The linear fit of the left graph is reported to the right graph for comparison.

### 3.3. Optical probe measurements

The optical probe was placed at a distance $x = 216$ mm from the most upstream part of the injector geometry, and was able to take measures in the following box: $-25.5 \leq y \leq 1.5$ mm and $52 \leq z \leq 102$ mm, considering that the origin $(y, z) = (0, 0)$ is the center of the vein, in $y$, at the height of the injection. To ensure a good detection of the diphasic flow, the acquisition for each measurement point lasted 20 seconds with a frequency of 1 MHz. A lower acquisition frequency, for instance 50 kHz, would still allow us to detect the phase changes and so the void fraction, but the size and velocity of the bubbles would have been inaccessible. The measurements were done for two different sets of experimental conditions $(D_{water}, D_{air})$ corresponding to a volumetric quality $\beta$ of 0.03 and 0.09.
and a theoretical water velocity \( U_{\text{water}} = \frac{D_{\text{air}}}{S\beta} \) of 1.25 m·s\(^{-1}\) with \( S = 170 \text{ cm}^2 \).

3.3.1. Void fraction  

The void fraction maps obtained are displayed in Figure 8. We can notice that the two-dimensional displacement, once symmetrized in \( y \), covers more than half of the bubble jet. However, we do not expect a symmetry of the map in \( z \) considering the gravity is \( z \)-oriented, so an extension of the measurement map would be an interesting future improvement.

As expected, the void fraction is globally higher when the volumetric quality is higher. Its 2-dimension map is of similar shape, even if a small shift of the peak can be observed from \( z = 57 \) to 62 mm when \( \beta \) rises from 0.03 to 0.09. In the \( y \)-direction, it can be well approximated with a gaussian centered on 0 and whose standard deviation decreases with \( \beta \).

![Figure 8: Void fractions at \( x = 216 \text{ mm} \) for a volumetric quality \( \beta = 0.03 \) (left) and \( \beta = 0.09 \) (right). The void fractions have been averaged between the two fibers and, for \( y \leq -4.5 \text{ mm} \), symmetrized to \( y \geq 4.5 \text{ mm} \). The resulting maps have been smoothed with a 3-by-3 gaussian blur convolution matrix.](image)

3.3.2. Bubble size and velocity  

From the experiments, after few filters to ensure the two optical fibers are measuring the same bubble, more than 10 000 acceptable bubbles remained for each volumetric quality \( \beta \). Their horizontal velocity \( U_x \) is displayed function of their diameter in Figure 9. We can notice, thanks to the moving average, a slight tendency of the smaller bubbles to be faster. Also, when \( \beta \) is higher, it seems that the bubbles are more sizable. However, the samples are very scattered as one can see with the high standard deviation of the moving average.

This trend is even more noticeable in Figure 10 where the mean diameter of bubbles are represented. The bubble sizes are nearly twice as big when the volumetric quality \( \beta \) rises from 0.03 to 0.09. It means that the air bubbles injected are more likely to coalesce when the air flow is important enough. On average, bubbles are between 5 and 25 mm, and we can see that the \( y \)-direction does not seem to affect it whereas the same cannot be said for the \( z \)-direction. Indeed, we can notice a small tendency of the bubbles to be a bit smaller at the top of the bubble cloud. That being said, a major improvement would be to have the bottom of the cloud to see the whole pattern, considering the bubble clouds seem to exist between \( 20 \leq z \leq 100 \text{ mm} \) for experimental conditions tested here.
**FIGURE 9:** Horizontal velocity $U_x$ of the bubbles function of their diameter at $x = 216$ mm for a volumetric quality $\beta = 0.03$ (left) and $\beta = 0.09$ (right). The moving averages are shown in green with their standard deviation in red. There are 24 500 bubbles at $\beta = 0.09$ and 10 750 at $\beta = 0.03$.

**FIGURE 10:** Mean diameter of bubbles at $x = 216$ mm for a volumetric quality $\beta$ of 0.03 (blue circles) and 0.09 (green squares), depending on the width $y$ (left) or the height $z$ (right) of the probe. The averages are shown in red.
4. Conclusion

An experimental apparatus has been designed to explore bubble cloud quality and air injection devices. It consists of a two-phase flow vein for water flow velocities up to 2 m·s\(^{-1}\) and volumetric qualities up to 30%. Several tools were used to describe flow quality. Direct flow visualization for an external view of bubble clouds, pressure sensors (Static pressure sensors and Pitot tubes) and an intrusive optical probe to get access to local void fraction, bubbles velocities and sizes.

Results obtained from the high speed camera allow to dress global patterns and shapes of bubbles clouds. High speed camera allow global patterns and shapes of bubble clouds to be identified.

Pressure measurements from static pressure sensors and pitot tubes allowed to assess pressure gains and losses induced by air injection on the global flow. First results show that changes in flow patterns are potentially revealed from pressure variation measurements. An important pressure drop due to the air orifice is observed between the air chamber and the vein. This was expected. Its cubic dependence with air flow rate requires further investigation to be fully explained.

Bubble clouds were also characterized thanks to intrusive measurements with an optical probe. Two-dimensional maps of void fractions, bubble sizes and velocities were made which enabled to identify some patterns. Nevertheless, this topic has numerous degrees of freedom, too many to be covered here. To follow up on this study, the evolution of the bubble clouds relative to the flow direction and the influence of the injector’s geometry could be interesting to look upon.

5. Acknowledgments

This work was sponsored by the NSERC - General Electric Industrial Research Chair in two-phase flow. Their support and permission to publish this paper is gratefully acknowledged. We also thank Prof. Jérôme Vétel for his contribution in experimental data acquisition and interpretation, and Ariane Benoit for her contribution in the optical fiber design and manufacturing.

References

[1] Florentina Bunea, S Houde, GD Ciocan, G Oprina, G Baran, and I Pincovschi. Aspects concerning the quality of aeration for environmental friendly turbines. In IOP Conference Series : Earth and Environmental Science, volume 12, page 012035. IOP Publishing, 2010.

[2] R Kumar and NK Kuloor. The formation of bubbles and drops. Advances in chemical engineering, 8:255–368, 1970.

[3] SC Chuang and VW Goldschmidt. Bubble formation due to a submerged capillary tube in quiescent and coflowing streams. Journal of basic engineering, 92(4):705–711, 1970.

[4] Hasan N Oguz and Andrea Prosperetti. Dynamics of bubble growth and detachment from a needle. Journal of Fluid Mechanics, 257:111–145, 1993.

[5] M Jamialahmadi, M R Zehtaban, H Miller-Steinhagen, A Sarrafi, and J M Smith. Study of bubble formation under constant flow conditions. Chemical Engineering Research and Design, 79(5):523–532, 2001. Fluid Flow.

[6] Daniel F McGinnis and John C Little. Predicting diffused-bubble oxygen transfer rate using the discrete-bubble model. Water research, 36(18):4627–4635, 2002.

[7] Iran E Neto, David Z Zhu, and Nallamuthu Rajaratnam. Air injection in water with different nozzles. Journal of environmental engineering, 134(4):283–294, 2008.

[8] Eizo Sada, Akira Yasunishi, Shigeo Katoh, and Masashi Nishioka. Bubble formation in flowing liquid. The Canadian Journal of Chemical Engineering, 56(6):669–672, 1978.

[9] I Chakraborty, G Biswas, and PS Ghoshdastidar. Bubble generation in quiescent and co-flowing liquids. International Journal of Heat and Mass Transfer, 54(21):4673–4688, 2011.

[10] Yoshinori Kawase and Jaromir J Ulbrecht. Formation of drops and bubbles in flowing liquids. Industrial & Engineering Chemistry Process Design and Development, 20(4):636–640, 1981.

[11] Hua Bai and Brian G Thomas. Bubble formation during horizontal gas injection into downward-flowing liquid. Metallurgical and materials transactions B, 32(6):1143–1159, 2001.

[12] Changjun Liu, Bin Liang, Shengwei Tang, and Enze Min. Effects of orifice orientation and gas-liquid flow pattern on initial bubble size. Chinese Journal of Chemical Engineering, 21(11):1206–1215, 2013.

[13] Frank M White. Fluid mechanics, WCB. 1999.