Developing a Combined Air Concentration and Velocity Probe for Measuring in Air-Water Jets

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Abstract

Air-water flows occur in numerous types of hydraulic structures, as well as in hydraulic machinery like the Pelton and the Cross-Flow turbines.

Due to the complexity inherent to the analytical and numerical study of highly turbulent air-water flows, experimental research has played a major role in the last decades, with the notable development of instrumentation techniques for measuring local air concentration and velocity, such as the electrical conductivity probes, fiber-optical probes and back-flushing Pitot tubes along with electrical conductivity probes. However, the application of these instruments is limited to situations where only a main flow direction exists which is known before the data acquisition. One example where such a priori knowledge does not exist is the flow inside and around the rotor of a Cross-Flow turbine.

In order to perform the simultaneous measurement of the magnitude and direction of the velocity vector for application to Cross-Flow turbines a three-hole probe with back-flushing, combined with an electrical conductivity probe, has been developed in the Laboratory of Turbo-Machinery of the Department of Mechanical Engineering of the Technical University of Lisbon, in cooperation with the Water Resources Research Laboratory of the Bureau of Reclamation, USA. In this paper, the instrument development and calibration will be discussed, with particular emphasis on the air concentration measurements.

Introduction

Air-water flows occur in numerous types of hydraulic structures, such as channels, weirs, spillways, and energy dissipators. Some hydraulic turbines like the Pelton and the Cross-Flow turbines also present this type of two-phase flow. Due to the complexity inherent to these air-water flows, the experimental research has been given a major role in the last decades, with the notable development of instrumentation techniques for measuring local air concentration and velocity, such as the electrical conductivity probes, fiber-optical probes and back-flushing Pitot tubes along with electrical conductivity probes (e.g. Frizell et al. 1994, Nagash 1994, Chanson 2002).

A known limitation of the previously mentioned instrumentation for measuring velocity is due to the a priori knowledge of the flow direction (e.g. Matos and Frizell 2000, Matos et al. 2002). Despite the recent developments with the laser velocimetry and PIV or ADV systems to analyze the flow field, their application is limited to situations where the air concentration does not exceed 5 to 10% (Amador 2005, Frizell 2000). However, there are situations where the direction of flow velocity vector is not known prior to the measurements and varies significantly, such as the flow inside and around the rotor of a Cross-Flow turbine (e.g., Haimerl 1960, Pereira and Borges 1996). In order to perform the simultaneous measurement of the magnitude and direction of the velocity vector for application to cases such as that above mentioned, a combined probe was developed which includes a three-hole cylindrical pressure probe, along with an electrical conductivity probe. Information on three-hole cylindrical pressure probes and several other types of aerodynamic probes for homogeneous flows can be found elsewhere (e.g. Bryer and Pankhurst 1971). Use of the three-hole cylindrical pressure probe in a two-phase flow requires back-flushing in all the holes, similarly to the back-flushing Pitot tube (e.g. Frizell et al. 1994, Matos et al. 2002). In addition, the estimation of the magnitude of the velocity vector requires the knowledge of the local air concentration. This is accomplished by an electrical conductivity probe, placed in the vicinity of the three-hole cylindrical pressure probe.

Combined probe

The Cross-Flow turbine rotor has a cylindrical drum shape and receives water from a nozzle with rectangular cross-section. The flow inside the rotor is usually considered two-dimensional, but the path across the rotor depends on the turbine operating conditions. The flow conditions inside the rotor change along the rotor periphery (e.g. Haimerl 1960, Durgin and Fay 1984, Fiuzat and Akerkar 1991, Fukutomi et al. 1991). In order to characterize the flow crossing the rotor it is necessary to use a probe with a well adapted geometry capable of measuring the velocity magnitude and angle in a specific location. The local air concentration must also be measured for determining the velocity magnitude because air will entrain as the flow crosses the rotor blades. Hence the conventional conductivity probe geometries cannot be used in this specific application. For this reason, a new probe configuration was developed, combining a three-hole cylindrical pressure probe and a conductivity probe in a single cylindrical rod. This apparatus can be mounted inside the turbine rotor, supported in both ends, moved along the rotor periphery and aligned with the flow direction. A schematic of the probe is presented in Figure 1.

The conductivity probe and the electronics control box were built at the Bureau of Reclamation (Reclamation), USA. The electronics control box produce an output signal from 0 to 5 volts depending on the air concentration in the air-water mixture where the platinum electrodes of the probe are located (Frizell et al. 1994, Jacobs 1997).

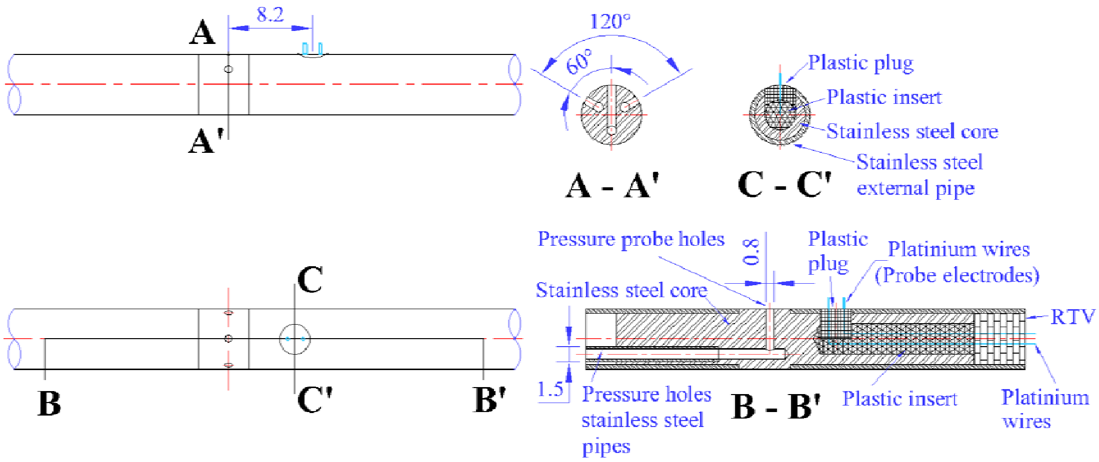


Figure 1 – Combined probe details.

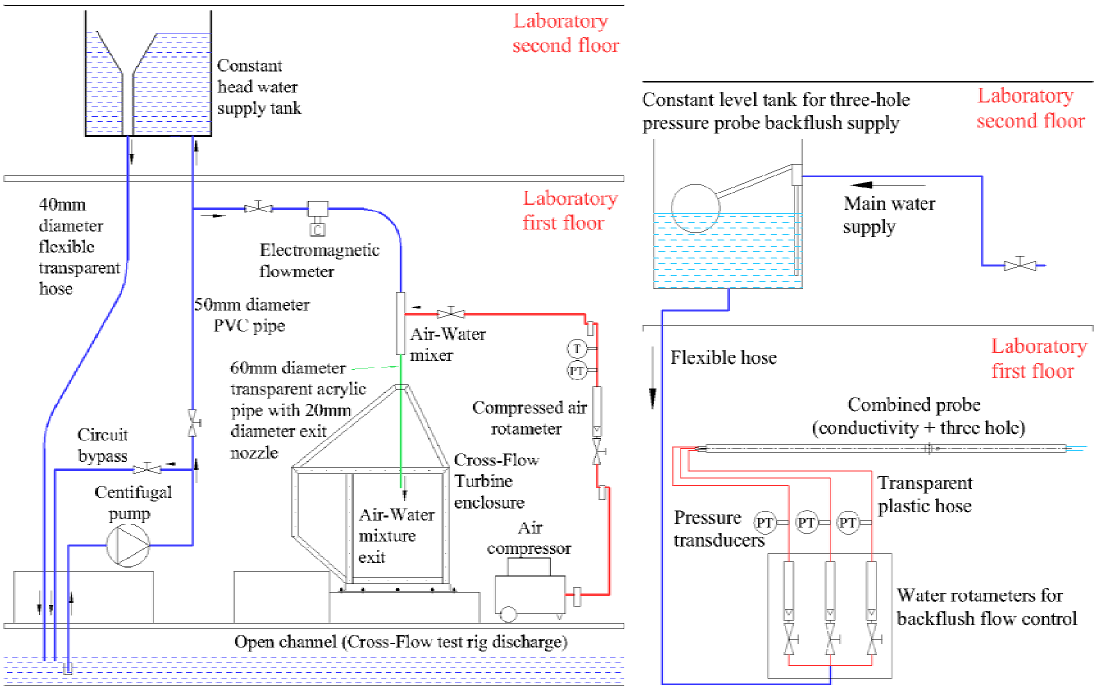
Calibration rig

The Cross-Flow turbine test rig was adapted to allow for the calibration of the combined probe (both conductivity and three-hole cylindrical pressure components) placed in a position similar to that adopted for flow measurements in the rotor. The type of water was identical to that used for flow turbine measurement, due to the common main water supply system. The principle of operation of the calibration rig is identical of that built at Reclamation (Frizell et al. 1994). A constant head water supply assures the flow steadiness, while an air compressor delivers the necessary air to mix with the water. An electromagnetic flowmeter is used to measure the water volumetric flow rate, while an air rotameter associated with a thermometer and a pressure transducer allow the determination of the air volumetric flow rate. The air is mixed in the water through a porous tube placed inside the water pipe. The air-water mixture passes by several stainless steel meshes and leaves the 60 mm diameter pipe through a 20 mm diameter exit nozzle. The distance between the nozzle exit and the combined probe can be adjusted. Figure 2 (a) includes a schematic of the calibration rig, and Figure 2 (b) illustrates the three-hole cylindrical pressure probe and respective back-flushing system.

This calibration rig is able to provide flows with any desired volumetric air concentration, ranging from clear water to entirely air flow conditions. However, a homogeneous mixture was not obtained for air concentrations larger than about 70%, similarly as observed by Frizell et al. (1994) in Reclamation's facility. In clear-water flow, the maximum velocity at the nozzle exit was around 9 m/s.

Conductivity probe calibration

The calibration of the conductivity probe was performed by comparing the volumetric air concentration imposed by the calibration rig with the output electrical signal of the probe. After some initial tests, the probe was positioned about 22.5 mm below the nozzle exit in order to assure atmospheric pressure at that given location. The probe signals were acquired using a National Instruments data acquisition board. Computational programs were developed in LabView programming language specifically for probe control and output signal acquisition and analysis. The conductivity probe electronics was always balanced in water prior to data acquisition. The mean output voltage from the electronics control box, multiplied by 20 leads to the percentage of the air concentration detected by the conductivity probe. Figure 3 shows the probe operating under distinct flow conditions.



(a) (b)

Figure 2 – (a) Sketch of the calibration rig; (b) three-hole cylindrical pressure probe and respective back-flushing system.

(a) (b)

Figure 3 – Combined probe testing: (a) clear-water flow; (b) air-water mixture.

The experimental data are plotted in Figure 4, along with the regression curves. This figure shows the reduced accuracy of the probe in detecting low air concentrations (i.e., lower than 10%). This may be due to the probe geometry, which causes flow stagnation in the electrodes region. The pressure increase in the vicinity of the measuring location is expected to move small air bubbles away from the tips of the probe. In the range 25% to 75% the probe has an almost linear response. For air concentrations above 70% the calibration rig is unable to provide a homogeneous flow, even though the probe signal was considered consistent.

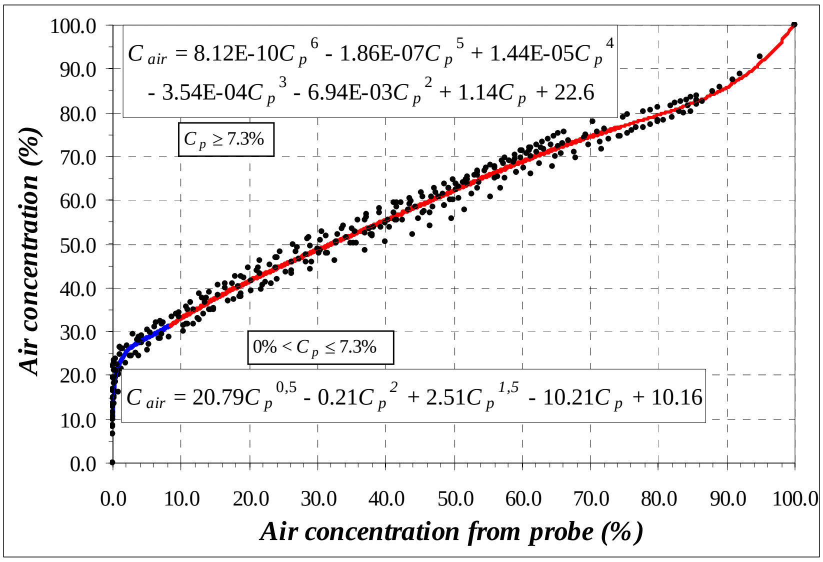
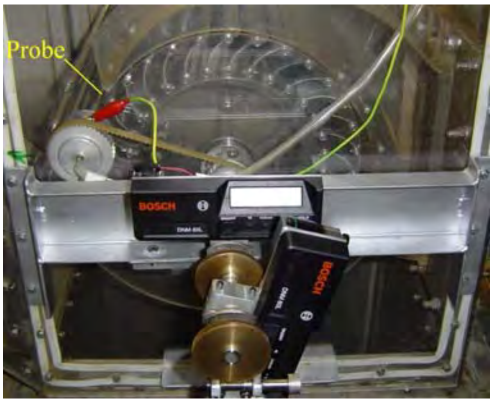
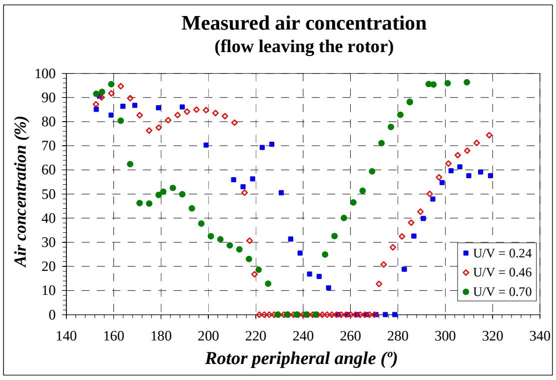


Figure 4 – Calibration curve of the conductivity probe.

Conductivity probe results

After concluding the conductivity probe calibration procedure, the probe was mounted for measuring in the outside region of the turbine rotor, as shown in Figure 5 (a). The air concentration measured outside the rotor is plotted in Figure 5 (b). In this figure, the peripheral angle is measured from the first quadrant horizontal axis. The operating condition defined for blade jet velocity ratio (U/V) equal to 0.46 refers to the maximum efficiency point, as per Pereira and Borges (1996). For all conditions, the measured air concentration in the central flow region was negligible (i.e., less than 10%), and it increased when the conductivity probe was moved towards the free surface. The extent of this lower air concentration region was found to be larger for peak efficiency conditions, as shown in Figure 5 (b).





(a) (b)

Figure 5 – (a) Combined probe positioned outside the Cross-Flow turbine rotor; (b) air concentration measurements for three different turbine operating conditions.

Conclusion

A new combined probe was developed to measure the velocity magnitude and direction in air-water flow in the rotor of a Cross-Flow turbine. The probe combined an electrical conductivity probe and a three-hole cylindrical pressure probe in the same cylindrical rod. The combined probe was calibrated and subsequently tested in the exterior diameter of the rotor, measuring air entrainment and velocity of the flow leaving the rotor. Further research will be conducted to deepen the knowledge on the calibration testing as well as on the flow behavior in the rotor of the Cross-Flow turbine.

Acknowledgments

The authors acknowledge the support granted by *Fundação para a Ciência e Tecnologia* (projects POCTI/EME/34146/99 and PTDC/ECM/73867/2006), as well as the Water Resources Research Laboratory of the U.S. Bureau of Reclamation, the IDMEC, the IST-UTL and the ESTSetúbal-IPS.

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