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Mass transfer studies across ventilated hydrofoils: A step towards hydroturbine aeration

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ABSTRACT

The water discharged by hydropower facilities is a matter of increasing concern due to poor downstream water quality. The use of auto-venting hydroturbines has been suggested as one of the best ways to mitigate low dissolved oxygen levels in the downstream water. Much of the design of auto-venting hydroturbines is currently performed with computational fluid dynamics (CFD) simulations. However, there is little information available to test and verify the performance of these simulations regarding gas transfer and bubble size distribution. This paper investigates the performance of a water tunnel test-bed for CFD simulations of an auto-venting hydroturbine through the use of a ventilated hydrofoil. Bubble size distributions are measured by a shadow imaging technique and found to have a Sauter mean diameter of 0.9 mm for a reference case. Higher liquid velocities, a lower airflow rate and a higher angle of attack all resulted in a greater number of small bubbles and a lower weighted mean bubble size. Bubble-water oxygen transfer is measured by the disturbed equilibrium technique. The gas transfer model of Azbel (1981) is utilized to characterize the liquid film coefficient for oxygen transfer, with one scaling coefficient to reflect the fact that characteristic turbulent velocity is replaced by cross-sectional mean velocity. The value of the coefficient is found to stay constant at a particular hydrofoil configuration while it varied over a narrow range of 0.52–0.60 for different hydrofoil angles of attack. This suggests that it is an appropriate coefficient for flow over a ventilated hydrofoil and possibly other flow situations. These results can be used by investigators to test and verify their CFD model against known bubble size distributions and gas transfer in a water tunnel flow that has important similarities to an auto-venting hydroturbine.

1. Introduction and motivation

Due to the depletion of fossil fuel supplies, global climatic changes and concern over nuclear waste management, the electric power industry is focusing attention on renewable energy technologies such as hydropower. Conventional hydropower has the potential to contribute a substantial portion of our energy requirements. However, the water discharged by hydropower facilities is of increasing concern due to its effect on downstream water quality [1,2]. This decreased water quality arises from two different mechanisms: increased dissolved gases such as nitrogen over high spillways and greatly diminished oxygen content in the water discharged from hydroturbines to the downstream environment.

The impoundments necessary for creating the hydraulic head to operate conventional hydroturbines can degrade water quality. The residence time of water within these reservoirs is long and processes such as respiration by aquatic plant and animal life, biodegradation of organic materials in the sediments, oxygen-consuming chemical reactions, etc. can decrease the DO levels, especially at greater depths (i.e. the hypolimnion) within the reservoir. Thermal stratification due to solar heating enhances conditions for low DO in the hypolimnion. Such a system, being hydrodynamically stable, inhibits mixing between layers and isolates the bottom water from atmospheric oxygen. Only surface waters are replenished with oxygen through gas transfer processes resulting from wave action [3]. Hydropower projects often have hydroturbine intakes located in the hypolimnion where DO levels may drop

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to anoxic conditions [4,5]. Hypolimnetic anoxia in turn leads to trace metals, nutrients, and hydrogen sulfide being released from sediments and a drop in the pH of the water endangering fish and other aquatic life in downstream rivers [6].

Often, air injection is suggested as a method to improve DO concentration in lakes and rivers [7–10]. Research on oxygen mass transfer between air and water has focused on free surface flows viz. gas transfer in spillway discharges [11–13]. The auto venting turbine (AVT) has been proposed as a cost-effective and promising technology that can be employed to mitigate the problems associated with low DO concentration in the hydroelectric releases [14,15]. The AVT is a self-aspirating hydroturbine designed to aerate the turbine discharge through ports located at low pressure regions which are connected to the atmosphere. Air released to the water from these ports breaks up into small bubbles due to the water's high velocity and turbulence. Oxygen transfer is augmented by the high interfacial area of these bubbles [16]. Relatively limited research has been undertaken on optimizing the performance of auto venting systems.

There are three important factors influencing the performance of an AVT: the quantity of entrained air, the bubble sizes and the rate of oxygen transfer from the bubbles. Further, computational models to study the impact of entrained air on the flow field and vice versa need to be developed. Such computational models need to quantify DO transfer as a function of flow conditions occurring in AVTs. To validate such a computational model, a dataset that allows quantitative analysis of aeration statistics for different hydroturbine blade hydrofoil designs is required. Such a dataset must provide information on bubble sizes, void fraction in the wake and the rate of oxygen transfer in the wake as a function of the different flow parameters. An aeration test-bed should be capable of testing these computational codes using configurations similar to an AVT. Such an aeration test-bed will advance the development and implementation of aerating hydroturbines at hydropower facilities, reduce the cost and regulatory uncertainty prior to hydropower development and enhance the aeration design capabilities.

In this study, a series of air injection experiments were conducted on a hydrofoil at several hydrodynamic conditions to investigate the effects of flow field on the size of the bubbles generated and the resulting rate of oxygen transfer. Experiments conducted to establish the methodology for creating a test bed were designed to study the impact of varying water velocities, airflow, and hydrofoil orientation (angle of attack) on the bubble sizes generated, void fraction in the wake, and oxygen transfer from the bubbles. A one-dimensional mass transfer model is developed to lend insight into the mass transfer characteristics observed in these experiments.

2. Description of experimental setup and methodology

2.1. Experimental apparatus

The experiments are conducted in the Saint Anthony Falls Laboratory (SAFL) high-speed water tunnel at the University of Minnesota [17,18]. As shown in Fig. 1, the tunnel has a horizontal test section of 1 m (length) × 0.19 m (width) × 0.19 m (height) with three side walls made of plexiglass for optical access. The tunnel is designed for cavitation and air ventilation studies and is capable of velocities in excess of 20 m/s. The gas collector dome (in the settling chamber) of the tunnel provides for the removal of large quantities of air injected as part of cavitation and ventilation experiments, thus allowing such experiments to continue for extended periods of time with little effect on test section conditions.

Validyne AP-10 absolute pressure transducers are used to measure absolute pressure in the test section and in the elbow vane downstream of the diffuser. A Validyne DP-10 differential pressure transducer is employed to measure the differential pressure between the settling chamber and test section and used to calculate test section velocity. The pressure transducers are calibrated before each series of experiments. The calibrations are performed using mercury manometer for both transducers. The pressure transducer calibrations are linear, with R-squared values typically 0.9999 or higher for both transducers. Standard errors of the pressure calibrations are approximately 0.1 kPa for both absolute pressure transducers. These errors lead to a maximum error in the measured velocity of 0.11 m/s, with typical errors being closer to 0.02 m/s [19].

A YSI thermistor probe is used to monitor water temperature in the water tunnel. An Omega Engineering FMA-2609A mass flow controller is used to set and measure airflow to the hydrofoil. Two Hach luminescent dissolved oxygen (LDO) probes and controller are used to measure DO concentration in both the settling chamber and the elbow vane downstream of the diffuser.

2.2. Hydrofoil and the flow conditions

During the experiments, a 2-D NACA0015 hydrofoil is installed horizontally in the test section and adjusted to one of three different angles of attack (α): 0°, 4° and 8°. The hydrofoil is 190 mm in span and 81 mm in chord. As shown in Fig. 2, a narrow spanwise slot allowed air to be injected into the flow near the leading edge of the hydrofoil on its suction side. For the gas transfer measurements, the full span length of the injection slot is used for air injection. This results in a dense spanwise bubbly wake. However, in order to make bubble measurements, ventilation is limited to a narrow 9.6 mm long slot section (5% of the full slot length) at the center of the span. This configuration ensures that bubbles remain within a narrow depth of field from the center of the test section. Videos of the bubbly wake verify that the lateral drift or spread of the bubbles is minimal. Silberman [20] investigated the production of bubbles by an orifice in liquid shear flows. His findings indicated that the bubble diameter depends only on air injection rate and water velocity, not on orifice size, as long as the gas issues as a jet from the orifice. Similarly, it is believed that the bubble sizes coming out of the injection slot are not dependent on the slot width. Since the injection slot width is constant in our experiments, it is reasonable to posit that the bubbles produced from the limited (5%) slot length are representative of the bubble population that exists when the full span is ventilated. For these bubble size analysis experiments, air flow rates were selected that were 5% of those used in the gas transfer testing. Thus, for any air flow test condition, the air flow rate per unit slot length was kept constant. Fifteen different experiments were conducted at test section water speeds of 5, 7.5 and 10 m/s, ventilation gas flow of 10, 20 and 30 LPM per unit span and hydrofoil angle of attack (AoA) of 0°, 4° and 8°. The bubbly wake images are obtained at 3 streamwise distances of 109, 243, and 377 mm downstream of the hydrofoil center (or 1.3, 3.0 and 4.7 times the chord length, respectively.) The resulting bubble diameters were close to the same, and the 377 mm location was chosen because it was believed to have the best view of the bubbles.

2.3. Experiment methodology: degassing and imaging

A disturbed equilibrium technique is used to estimate gas transfer rates by initially degassing the water to the lowest level possible and then reoxygenating the water while taking continuous DO concentration measurements [21]. During deoxygenation, a portion of water is withdrawn from the tunnel and circulated through