Ocean Engineering 169 (2018) 1–18

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Large eddy simulations of ventilated micro hydrokinetic turbine at design and off-design operating conditions

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ARTICLE INFO

*Keywords:*
Micro hydrokinetic turbine
Large eddy simulation
Flow separation
Aeration
Multiphase flow
Mixture multiphase model

ABSTRACT

Multiphase large eddy simulations (LES) were conducted for ventilated micro hydrokinetic turbine operating at design and off-design operational conditions. The simulations were performed with and without aeration at the design tip-speed ratio of 1.86 and at off-design tip-speed ratios of 1.2 and 2.7. The spatial and temporal characteristics of oxygen dissolution into the water were examined. The nominal value of power generation for the tip-speed ratio of 1.2 decreased slightly with aeration, while it increased slightly at the tip-speed ratio of 1.86 and 2.7. Slight increase in thrust was also observed for each case. The standard deviation of both power and thrust coefficient were increased more than 47% with air injection at the tip-speed ratio of 1.2, while the standard deviation of the thrust coefficient decreases by approximately 18% at the tip-speed ratio of 1.86 and 2.7. The suppression of small eddies and the early dissipation of tip vortices in multiphase simulations in the cases of the tip-speed ratio of 1.86 and 2.7 can be related to more stable turbine operation with aeration. It is demonstrated here that micro hydrokinetic turbines can be used effectively for aeration purposes at wide range of operating conditions.

## 1. Introduction

Water is the most essential compound responsible for the life and the ecological balance on earth. Conservation of the water quality is crucial for the sustainability and the health of each lifeform in the ecosystem. Water quality can be evaluated based on several parameters such as dissolved oxygen (DO), salinity and pH level. The amount of dissolved oxygen in water is a crucial water quality indicator. The marine organisms including fish, bacteria and underwater plants need dissolved oxygen during respiration; same as land organisms. The marine bacteria and fungi use oxygen in decomposition process of organic compounds that create carbon dioxide, water and nutrients. One criterion for the level of dissolved oxygen is stated by U.S. Environmental Protection Agency (EPA) as follows: not less than 3 mg/l for fish survival and not less than 6.5 mg/l as a 30-day average for fish reproduction (Bunea et al., 2014). Low quantity of dissolved oxygen leads to other water quality problems as trace metal dissolution, hydrogen sulfide formation, and pH value reduction in the water (Wilhelms et al., 1987).

The water passing through the hydro turbines in dams contains a low amount of dissolved oxygen and is considered as the primary reason for decreased water quality in rivers. During the summer seasons, the water in reservoirs is divided into different layers based on their DO content. The layers close to the free surface contain higher DO level, and its amount reduces as the water depth increases. Generally, the turbine intakes are located far away from the free surface, and the turbines discharge water with low DO content to the downstream of the plant. The most popular method to address this issue is to aerate water during the discharging process from the turbine. A total of 178 turbines at 58 hydropower facilities in the U.S. provide aeration and 137 of them are vertical Francis turbines with a capacity greater than 5 MW (March and Jacobson, 2015).

Prior studies of ventilated hydrofoil and full hydro turbine are focused on the bubble size, the dissolved oxygen concentration and the impact of aeration on turbine efficiency. Experimental analyses of ventilated hydrofoil are conducted by Karn et al. (2015a, 2015b, 2016) in a closed loop water channel to study aeration capabilities of hydrofoil quantitatively. Their experiments reveal that an increase in water velocity results in greater bubble breakup while an increase in air injection rate leads to greater bubble coalescence in the hydrofoil wake region (Karn et al., 2015a). Moreover, altering the angle of attack from $0^\circ$ to $8^\circ$ favored smaller sized bubbles (Karn et al., 2015b). Their

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https://doi.org/10.1016/j.oceaneng.2018.09.008
Received 24 October 2017; Received in revised form 10 August 2018; Accepted 1 September 2018

**Nomenclature**

| | |
|---|---|
| $C$ | molar concentration, mol/m$^3$ |
| $d_S$ | Sauter mean bubble diameter, m |
| $D$ | diffusion coefficient, m$^2$/s |
| $DO$ | dissolved oxygen, mg/l |
| $g$ | gravity, m/s$^2$ |
| $He$ | Henry constant, Pa |
| $k_l$ | liquid side mass transfer coefficient, m/s |
| $M_{o_2}$ | molar mass of oxygen, kg/kmol |
| M | meridional length, m |
| $\dot{m}_{gl}$ | mass transfer from gas phase to liquid phase, kg/m$^3$s |
| $\dot{m}_{lg}$ | mass transfer from liquid phase to gas phase, kg/m$^3$s |
| $N$ | number of cells |
| $P$ | partial pressure, Pa |
| $p$ | pressure, Pa |
| $Re$ | Reynolds number |
| $S$ | strain tensor, 1/s |
| $SGS$ | subgrid scale |
| $Sc$ | Schmidt number |
| $Si$ | sink term, 1/ms |
| $So$ | source term, 1/ms |
| $T$ | thrust, N |
| $T$ | time, s |
| $U$ | velocity, m/s |
| $x$ | mass fraction |
| $y$ | molar fraction |
| $y^+$ | dimensionless wall distance |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | volume fraction |
| $\alpha_i$ | interfacial area concentration, 1/m |
| $\beta$ | relative flow angle, ° |
| $\beta'$ | blade angle, ° |
| $\Delta$ | change in variable |
| $\varepsilon$ | permutation symbol |
| $\theta$ | wrap angle, ° |
| $\mu$ | dynamic viscosity, kg/ms |
| $N$ | kinematic viscosity, m$^2$/s |
| $\rho$ | density, kg/m$^3$ |
| $\Sigma$ | solidity |
| $T$ | stress tensor, kg/ms$^2$ |
| $\omega$ | angular velocity, rad/s |
| $\tilde{\omega}$ | normalized vorticity |

*Superscripts*

| | |
|---|---|
| $\sim$ | normalized |

*Subscripts*

| | |
|---|---|
| $dr$ | drift |
| $g$ | gas phase |
| $g, l$ | gas or liquid phase |
| $i, j, k$ | tensor indices |
| $L$ | liquid phase |
| $M$ | mixture |
| $O_2, eq$ | property of oxygen in liquid phase at equilibrium |
| $O_2, g$ | property of oxygen in gas phase |
| $O_2, l$ | property of oxygen in liquid phase |
| $Slip$ | relative between phases |
| $T$ | turbulent |
| $TI$ | turbulent impact |
| $WE$ | wake entrainment |
| $RC$ | random collision |
| $\mu$ | viscous |
| $\infty$ | free-stream |

measurements reveal that the breakage effects are dominating throughout the near wake region while the coalescence effects are much more intensive within the far wake region (Karn et al., 2016).

In addition to the experiments of the single ventilated hydrofoil, aeration is investigated for full hydro turbines to study the influence of air introduction on oxygen dissolution and turbine efficiency. Auto venting aeration technology is applied for two units at Norris Dam using different aerating technologies as central, distributed and peripheral aeration. The study reveals that the single unit can increase the zero incoming DO level up to 5.5 mg/l with combined operation of aeration options. The typical turbine efficiency loss at Norris ranges from −0.2% to 4.0% and the impact of aeration on turbine efficiency from highest to lowest is arranged as central, peripheral and distributed aeration (March and Fisher, 1999; March 2011). Harshbarger et al. (1999) reports the modifications made for existing aerating turbines at Bull Shoals, Norfolk and Table Rock Dams to enhance the dissolved oxygen level in the turbine discharges. After the modifications, induced air flow is increased at each dam as intended and that behavior resulted in DO uptakes of 2–3 mg/l at Bull Shoals, 2.5–3 mg/l at Norfolk and 2–3 mg/l at Table Rock Dams for single unit operation. Changes in power generation due to the modifications were negligible.

Moore (2009) describes the aeration system installation to three turbines at Lloyd Shoals Dam located in Georgia to meet state DO criteria. The draft tube aeration provided the desired amount of DO level and the pre-installed aerating weir, which requires costly repairs, are removed. After the installation of aeration systems, a minor reduction in turbine efficiency is observed. The elevated DO level also decreased the dissolved manganese concentration in the river which otherwise needed to be removed during water treatment process. Papillon et al. (2002) provide experimental test results of central and peripheral turbine aeration. The air introduced from the center of the runner cone formed a central vortex core while the peripheral aeration technique provided well-distributed, small-sized bubbles that yields higher oxygen dissolution rate. They also reported that the influence of the peripheral aeration on efficiency is much lower than that of central aeration.

Although low dissolved oxygen problems can be solved using ventilated hydro turbines, only a small percentage of the dams in the U.S. involve aerating turbines. Another solution to enhance the dissolved oxygen in the water streams is to aerate water through hydrokinetic turbines. Hydrokinetic turbines operate underwater and use the kinetic energy of streaming water to generate power. Compared against conventional hydropower plants that use the potential energy of water, micro hydrokinetic turbines are portable, do not require additional large constructions such as dams, and do not alter the nature of water streams. The estimated potential generation capacity increase of hydrokinetic energy technology in the U.S. is 3000 MW by 2025 (Electric Power Research Institute (EPRI), 2007). In the present study, water aeration is investigated using a pre-designed micro hydrokinetic turbine for river applications (Schleicher et al., 2015).

The main goal of the present numerical study is to aerate water through the hydrokinetic turbine while the turbine is generating power at turbine's best efficiency and off-design operating conditions. Generally, the turbines are desired to operate at best efficiency point to extract the maximum energy from the water. However, the hydrokinetic turbine designed for river applications might experience off-design operation based on the variable river flow speeds. This study presents large eddy simulations of the turbine operating at three