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Computational study of aeration for wastewater treatment via ventilated pump-turbine

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A R T I C L E I N F O

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A B S T R A C T

Large eddy simulations were performed on a modular pump-turbine to study oxygen dissolution inside the draft tube. Air injection was applied over the runner cone surface during turbine operation. Data regarding bubble size, void fraction and interfacial area concentration were presented to understand their influence on oxygen dissolution. Transient single phase and multiphase flow simulations were carried out to investigate the influence of air injection and dissolution within the flow field and turbine performance. Multiphase simulations were conducted by using the mixture multiphase model. The mathematical modeling of oxygen dissolution employed was validated by comparing predicted oxygen dissolution against experimental measurements performed by Zhou et al. (2013). The averaged dissolved oxygen concentration in the range of 1.2–1.4 mg/l was obtained; which is sufficient for an active aerobic microorganism activity for wastewater treatment processes. Dissolution efficiency and the amount of averaged dissolved oxygen inside the draft tube were sensitive to the inlet bubble size. The efficiency of the dissolution increases strongly as the inlet bubble size was reduced. The obtained results revealed that vortex suppression was achieved through air admission within multiphase flow simulation. Moreover, the power generation of the turbine was hardly influenced by the aeration through the runner cone.

1. Introduction

Maintaining water quality is essential for ecological systems and sustainable utilization of water. Wastewater requires proper treatment before it is released into the environment. The wastewater treatment process consists of two stages: a primary and secondary stage. In the primary stage, suspended solids are removed physically with screens and skimming. The secondary stage involves biological treatment in which the micro-organisms convert the organic matter such as ammonia into inorganic compounds such as carbon dioxide and water. The United States Environmental Protection Agency (EPA) states that almost 90% of the organic waste in wastewater is removed by the secondary stage (E.P.A., 2004). The micro-organisms need dissolved oxygen (DO) in the facility during the treatment process to decompose the organic wastes.

In the present study, numerical analyses are performed to study aeration for wastewater treatment via a pumped-storage scheme by injecting air into the draft tube during turbine operation. Simulations are conducted for a modular pumped-storage scheme with and without aeration. The purpose of this work is two-fold: i) to determine the effectiveness of aeration for wastewater treatment using pump-turbines and ii) to evaluate the effect of aeration on the pump-turbine performance.

There are numerous analytical, numerical and experimental studies considering oxygen dissolution, mass transfer and wastewater treatment in different systems. Bubble columns (Buscaglia et al., 2002; Gong et al., 2009) and stirred tanks (Chen et al., 2003; Kerdouss et al., 2006; Min et al., 2008) provide enhanced mass transfer or mixing performance in chemical, biochemical and environmental applications. Buscaglia et al. (2002) studied air dissolution in water in a bubble column by employing both one-dimensional analytical and two-dimensional computational fluid dynamics (CFD) approaches. They compare the liquid velocity, the bubble size, the gas holdup of each species and the air dissolution rate predicted by analytical and numerical solutions with good agreement. Chen et al. (2003) studied the oxygen dissolution in an agitated tank to reveal the influence of the agitation speed, the temperature, the working liquid level and the pressure on oxygen volumetric mass transfer coefficient. In their experiments, they considered the pressure in the range of 1–1.2 atm and the temperature in the range of 20-40 °C. They reported that the

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Nomenclature

B	gate height, mm
C	molar concentration, mol/m^3
d_i	inlet bubble diameter, m
d_S	Sauter mean bubble diameter, m
D	diffusion coefficient, m^2/s
D_{ref}	reference diameter, m
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
$\dot{m}_{gl}$	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	rotation speed, rpm
P	partial pressure, Pa
p	pressure, Pa
Q	Q-criterion, 1/s^2
$\dot{Q}$	flow rate, m^3/s
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	time, s
$\vec{U}$	velocity, m/s
x	mass fraction
y	molar fraction
y^+	dimensionless wall distance

Greek Symbols

α	volume fraction
α_i	interfacial area concentration, 1/m
Δ	change in variable
σ	standard deviation
θ	wrap angle, °
μ	dynamic viscosity, kg/ms
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
Ω	rotation tensor, 1/s
τ	stress tensor, kg/ms^2

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
s	subgrid
slip	relative between phases
T	turbulent
TI	turbulent impact
WE	wake entrainment
RC	random collision
μ	viscous

increase in the agitation speed, the temperature and the decrease in working liquid level elevates the volumetric mass transfer coefficient. The pressure does not affect the volumetric mass transfer coefficient, however higher pressure provides higher equilibrium DO concentration.

The effect of the bubble size in the flow domain must be considered to predict the oxygen dissolution accurately. Kerdouss et al. (2006) carried out numerical analysis to obtain bubble size and gas volume fraction in a stirred tank. Bubbles with smaller size are obtained around the impeller discharge due to bubble breakage by small size eddies induced by impeller. Min et al. (2008) conducted simulations considering a constant bubble size and a variable bubble size in a stirred tank. Their study reveals that constant bubble size assumption ignoring the breakage and the coalescence effects is not capable to predict local gas hold up accurately. Their results obtained with the variable bubble size assumption are consistent with the prior experimental findings.

In stirred tanks, additional power is required to rotate the impeller for mixing purposes. Therefore, aerating the hydro turbines becomes more attractive due to turbulent momentum mixing naturally induced by the turbine. Karn et al. (2015) studied the bubble size characteristics as a function of Reynolds number and air flow rate in the wake of a ventilated hydrofoil. They determined that higher Reynolds number elevates the bubble breakage effects whereas higher air flow rate leads to increase in the bubble coalescence effects in the hydrofoil wake. Karn et al. (2016) introduced a dispersion theory to calculate bubble size and demonstrated good agreement compared to experimental observations in a breakup dominated region within low air injection rate. They observed greater breakup events in the close wake region and greater coalescence effects in the far wake region. The aeration of the water flowing through a Francis turbine was studied by Papillon et al. (2002) experimentally. They compared the air admission ability and the effect of aeration on turbine efficiency for different air admission systems: air admission by runner cone and air admission by discharge ring. They concluded that the air admission at the runner cone is generally easier than that at the discharge ring due to a lower pressure at the air admission location. They observed an increase in the turbine efficiency for low air flow rates (less than 1% of water flow rate) and a decrease in the efficiency for higher air flow rates in the case of runner cone aeration. However, the turbine efficiency is hardly changed by air flow rate in the case of ring aeration.

Oxidation ditches are typically used to treat wastewater. Yang et al. (2011) conducted numerical simulations of oxidation ditch for different operating conditions to investigate the impact of operating conditions on the energy consumption and the treatment efficiency. They compared the numerical predictions of the flow field and the DO concentration against actual measurements. Lei and Ni (2014) performed three-phase simulations including water-gas, water-sludge and gas-sludge interactions to study the oxygen dissolution, carbon oxidation, and nitrification/denitrification processes in an oxidation ditch. They compared their numerical results of aforementioned water quality parameters to experimental measurements and reported good agreement. They also revealed the significant influence of impellers and stirrers on mixing. Oxidation ditches have been commonly used in wastewater treatment facilities due to their simplicity, low sludge production and low cost (Hong et al., 2003). However, oxidation ditches occupy large space and require considerable amount of energy (Yang et al., 2011).

In this study, predesigned and optimized modular pump-turbine is used to treat wastewater during the turbine operation. This work not only investigates aeration characteristics for potential application as a wastewater treatment but also studies the energy storage solution through the pump turbine. Pump-turbines are typically used for energy storage in conjunction with intermittent energy sources, such as wind and solar power; allowing for uninterrupted power generation to the