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Oxygen transfer and power consumption in an aeration system using mist and circulation flow generated by a rotating cone

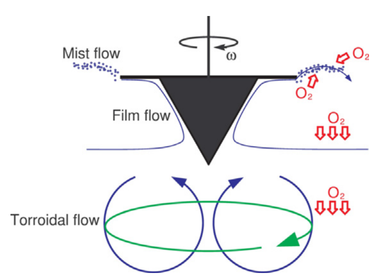
Takahiro Adachi *

Department of Mechanical Engineering, Akita University, Tegata-Gakuen 1-1, Akita 010-8502, Japan

HIGHLIGHTS

- Liquid thin film flow is generated only by rotating a cone immersed in the water.
- Mist flow is also generated by the rotating cone, which is a very easier technique than existing ones.
- The mist flow is effective for oxygen mass transfer from the air to the water.

GRAPHICAL ABSTRACT



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ABSTRACT

We have experimentally found the liquid film flow characteristics rising along the outer surface of a rotating cone. When the film flow goes up fully upward, the liquid film cannot keep the filmwise condition and is eventually atomized into a mist flow. In this research, we apply the mechanism to atomize the liquid and to transport oxygen from the air to the water through the atomized water droplets. It is recognized that the mixing is effective in oxygen mass transfer. It is found that a dual effect of the mixing and mist flow by using a rotating cone increases the oxygen mas7s transfer because the mist flow has a small diameter and large surface area between liquid and gas. In addition, the flow pattern is changed from steady flow to unsteady one if the rotation rate increases further, where the oxygen mass transfer is slightly enhanced. Furthermore, a correlation between the unit volume power consumption and the oxygen mass transfer is examined and shows that the oxygen transfer increases in power law relationship with the unit volume power consumption in the case with the mist flow.

1. Introduction

In closed water systems such as dams, lakes and marshes, the water in the surface layer is warmed by thermal radiation from the sun and stays in the top layer. Therefore, a warm surface layer is established on the top, while a relatively cold layer is inevitably established at the bottom. Consequently, the warm water remains in the surface layer and the cold water in the bottom one, since a thermal stratification is formed in the vertical direction. In such a situation, organic nutritive elements like phosphorus and nitrogen are increased in the surface layer and eutrophication is enhanced, which leads to occurring of algal blooms in the water. Eventually, the water quality gets worse due to a bad smell, muddiness, and so on. An efficient solution to make the water quality better is to improve purification ability of nature by activating an ecological system inside the closed water area. This implies that a concentration of dissolved oxygen must be increased by promoting a mass transfer of oxygen from the air to the water.

Aeration plays an important role in enhancement of the oxygen mass transfer. Many different types of aeration systems have been developed over the years. It is common in the aeration to pass the air through the water with the Venturi tube, aeration turbines,

* Tel.: +81 18 889 2306; fax: +81 18 837 0405.
E-mail address: adachi@ipc.akita-u.ac.jp

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compressed air, etc. In order to evaluate the performance of different types of aeration systems, a standard for the measurement of the oxygen transfer in clean or tap water is established by American Society of Civil Engineers (ASCE, 2006) based on the basic model of Brown and Baillod (1982), where the standard describes in detail the experimental apparatus and methods, and recommends the standard conditions such as zero dissolved oxygen level, 20 °C water temperature and 1 atm pressure.

On the studies using air bubbles for aeration, Ashley et al. (1992) have studied bench-scale study of oxygen transfer in coarse bubbles, while Duchene et al. (2001) have focused on fine bubbles for the aeration. A range of diameter of coarse bubbles is between 6 and 10 mm and one of fine bubbles is between 2 and 5 mm. They showed that these bubbles were easy to create without much power and energy, and effective for the aeration. Chen et al. (2003) have investigated an aeration process to obtain high oxygen dissolution applying a gas-inducing reactor, where pure oxygen was introduced into the reactor and was stirred with 6-blade pitched-blade downward turbine. They obtained a correlation regarding agitation power consumption and oxygen mass transfer coefficient. In addition, Yamada et al. (2005) have proposed a method to improve the water quality using micro-bubbles whose sizes are micro-order. They studied the relation between distributions of micro-bubbles and dissolved oxygen concentrations, and showed that the method using micro-bubbles was by far advantageous to supply oxygen into the water. It should be noted, however, that a large quantity of energy must be required to create the micro-bubbles. Furthermore, Chen and Yu (1997) have tried to estimate an emission rate of volatile organic compounds instead of the water from the aeration systems. Chern et al. (2001) and Rosso and Stenstrom (2006) have studied effects of impurities and surfactants on the oxygen transfer rate.

As mentioned above, the aeration systems which directly pass the air into the water have been extensively investigated. Contrary to the aeration systems using air bubbles, several attempts have been made for liquid surface aeration. Srinivasan and Aiken (1988) have investigated the mass transfer and physical absorption in liquids dispersed as droplets in a gas. The droplets were formed by the break up of a cylindrical jet with a complex and turbulent mechanism. They claimed that the convection due to the formation process significantly enhanced mass transfer. Mcwhirter et al. (1995) have developed a fundamentally rigorous oxygen mass transfer model using surface aerator with aerator blades. The model separated the oxygen transfer process into a liquid spray mass transfer zone and a surface reaeration mass transfer zone, which was able to provide the methodology and techniques for quantitatively determining the oxygen transfer rate within each of these important but fundamentally different oxygen mass transfer zones. Chern and Yang (2004) have studied oxygen transfer rate in a tank with water in a drop structure, where the water droplets were generated from a nozzle and a recirculation was established because the water was supplied by pumping up into the nozzle. They examined semiempirical equations to correlate the parameters of the suggested oxygen model as functions of water recirculation rate, drop height, water depth and temperature.

In this study, we use a mist flow composed of smaller water droplets for the aeration. It is common to use a liquid jet from a nozzle driven by a high pressure generated with devices such as fans, compressors, pumps and so on. However, the system based on the liquid jet becomes large and inefficient because these several devices are needed. In addition, it is difficult to control the characteristics of the atomization, i.e. droplet diameter, quantity of the mist flow, etc. Therefore, a new atomization system for generating droplets is required, which should be compact, electricity saving and easily controllable. We propose a new atomization system which uses an interesting flow phenomena that the liquid comes rising along the outer (not the inner) surface of a rotating cone, where the cone is immersed in the liquid by turning the top upside down. The liquid rising along the outer surface becomes thinner and forms a film flow, leading to atomization of the liquid. We call the interesting flow phenomena a pumping-up mechanism caused by the rising film flow. Indeed, it is comprehensible and well known that the liquid rises along the inner surface of a rotating hollow cone due to the centrifugal force (Bruin, 1969; Makarytchev et al., 1997, 2001), but there is only a research of Adachi et al. (2010a,b) on the phenomena that the liquid rises along the outer surface of the rotating cone and does not separate from the surface. Recently, Adachi (2013) and Adachi

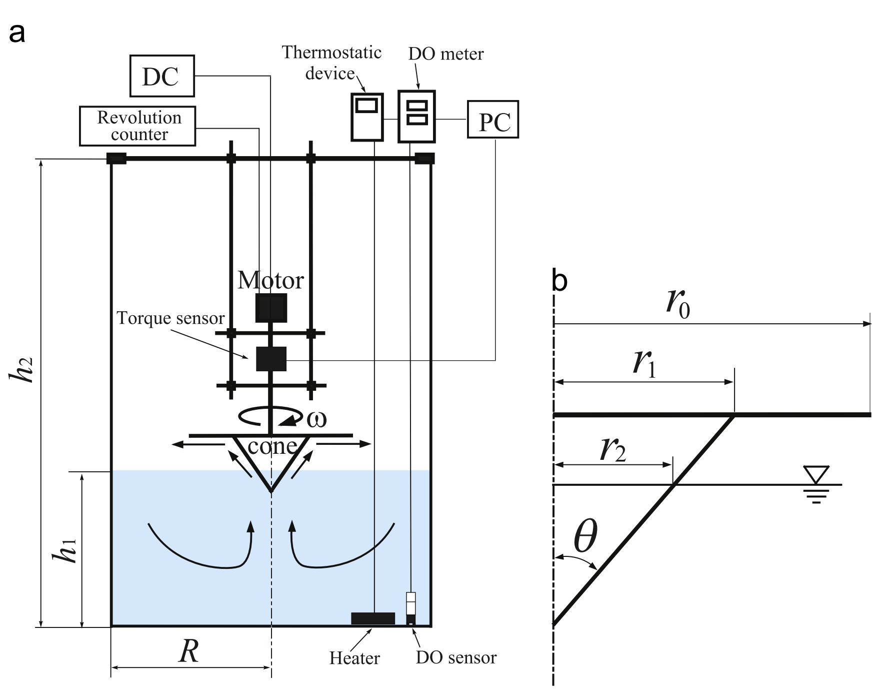

Fig. 1. Experimental apparatus.