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A FLOAT-TYPE WATER PURIFIER WITH MIST GENERATED BY ROTATING CONES

PŁYWAJĄCE URZĄDZENIE DO OCZYSZCZANIA WODY WYKORZYSTUJĄCE MGŁĘ WYTWARZANĄ PRZEZ WIRUJĄCE STOŻKI

We have experimentally found the liquid flow characteristics of the rising film flow along the outer surface of the rotating cone. Generally, one can imagine that the film flow separates and scatters from the surface of the cone because a centrifugal force acts on the liquid film in the outward radius direction due to the rotation of the cone. However, the centrifugal force lifts up the liquid, which is called a pumping-up mechanism in this study. In addition, the surface tension etc. acts on the outer surface of the liquid film and works to maintain the liquid film on the surface of the cone because the surface tension acts in the inner radius direction. This mechanism is used in a new device to atomize liquid and generate mist flow. Namely, the liquid film is atomized eventually into mist flow. In this research, we apply the new atomization process to a purifier and investigate mist type purifier using pumping-up mechanism generated by thin film flow.

1. Introduction

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, 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) based on the basic model of Brown and Baillod[1], 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[2].

On the studies using air bubbles for aeration, Ashley et al.[3] have studied bench-scale study of oxygen transfer in coarse bubbles, while Duchene et al.[4] have focused on fine bubbles for the aeration. A range of diameter of coarse bubbles is between 6-10 mm and one of fine bubbles is between 2-5 mm. They showed that these bubbles were easy to create without much power and energy, and effective for the aeration. On the other hand, Yamada et al. [5] 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.

As mentioned above, the aeration systems which directly pass the air into the water have been extensively investigated. Contrary to the existing systems, we will try to use a mist flow composed of water droplets for the aeration in this study. 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 film. 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[6,7], but there is only a research of Adachi et al.[8] on the phenomena that the liquid rises along the outer surface of the rotating cone and does not separate from the surface. In addition, Adachi[9] has investigated an enhancement of oxygen dissolution using the pumping-up and mist flow mechanism generated by the rotating cone.

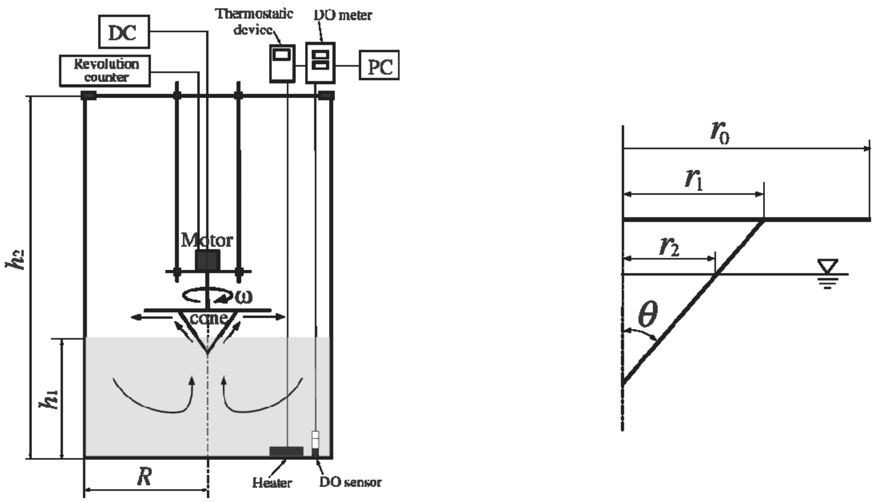
In this paper, we experimentally investigate the mist type purifier which uses the pumping-up mechanism caused by the rising film flow along the outer surface of the rotating cone. First, we show the results of the visualization of the interesting flow phenomena along the cone with a high-speed video camera. Then, the dissolved oxygen concentrations are measured and the oxygen mass transfer coefficients are calculated using the measured date.

2. Experimental Setup

Figure 1(a) shows the experimental apparatus. In the test section, a cone is set at the center of a circular tank with an inner radius of R=360 mm, h_2=900 mm and filled with municipal tap water of a height of h_1=140 mm(about 50 l) as a working fluid. Dimensions of the cone are shown in Fig. 1(b), where a half tip angle is θ = 30° and a maximum radius at the bottom of the cone is r_1 =30 mm. The cone is connected to a disk with a diameter of r_0=150 mm and 1 mm thickness. The disk is useful for making the liquid droplets much smaller. It should be noted that the quality of the material of the cone is an Acrylonitrile Butadiene Styrene (ABS) copolymer and a special treatment is not given to the surface of the cone, where the arithmetic surface roughness is Ra=1.6 [μm].

The cone is immersed in the water such that the immersed radius is r_2=16.5 mm. When the cone rotates, a film flow of the water rises along the outer surface of the cone and reaches the base of the cone. After that, the film flow goes along the upper disk connected to the cone and radiates outward being atomized.

At the beginning of each test run, the sodium sulfite of 10 g is added as a deoxidizer to the tap water of 50 l and the cone is rotated with a lower rotation rate until the dissolved oxygen reaches zero level. After that, the concentration of dissolved oxygen in the test section is measured by using a DO meter (OM-51, Horiba Inc. Japan) whose probe is put under the water beside the side wall as seen in Fig. 1(a). The sampling rate of the DO meter is set up 1/60 Hz. The operation temperature of the water inside the tank



(a) (b)

Fig. 1 Experimental apparatus

is maintained to be 20±1 °C with a thermal controller and a heater, because a saturation concentration of the dissolved oxygen changes depending on the water temperature.

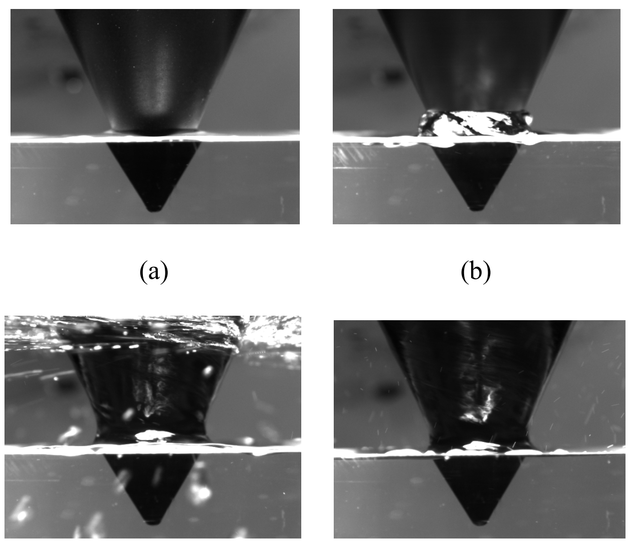
3. Results

3.1. Visualization of Rising Film Flow and Circulation

Thin liquid film flow rising along the outer surface of the cone is generated when the immersed cone rotates in the circular container. We visualize the phenomena with a high-speed video camera. Flow patterns of the rising film flow are shown in Fig. 2, where a rotation rate of the cone is gradually changed from $\omega = 0$ to 6000 rpm. Figure

2(a) shows an initial state where the cone is in a state of rest. Once the cone begins to rotate, water is deformed and lifted up at the vicinity of the cone surface as seen in Fig. 2(b). However, the water does not go up anymore at that time because the rotation rate is small. When the rotation rate is further increased, the deformation of the water becomes larger as seen in Fig. 2(c), and the water surface winding around the cone rises higher due to the larger degree of the deformation caused by the lifting up. After that, a mass of water is scattered out radially in radius and tangential directions. Subsequently, a thin liquid film flow is generated which rises along the outer surface on the cone as seen in Fig. 2(d). The film flow cannot keep the filmwise condition and is eventually atomized into a mist flow when the film flow goes up further, although it does not separate from the cone surface. In this study, the cone is connected to the circular disk and the film flow goes along the disk being thinner, which is useful for making the liquid droplets much smaller.

In addition, a visualization photograph under the cone inside the water is shown in Fig. 3. We can see a strong vortex filament along the central axis of the rotating cone, where an upward flow is generated due to a spin-up of the rotation of the cone. A part of the upward flow goes up along the cone outer surface to generate the rising film flow. The other part of the upward flow goes along the water surface outward the circular tank, goes down into the bottom along the side wall and converges to the center along the bottom wall. After that, the flow is going up again generating the vortex filament along the central axis. It should be noted that the so-called Ekman layer is formed on the water surface and the bottom wall, while the Stewartson layer on the side wall. Therefore, there is a large circulation like a torus inside the water under the cone, which is effective for transport processes.



(a) (b)

(c) (d)

Fig. 2 Visualization photographs of the rising film flow

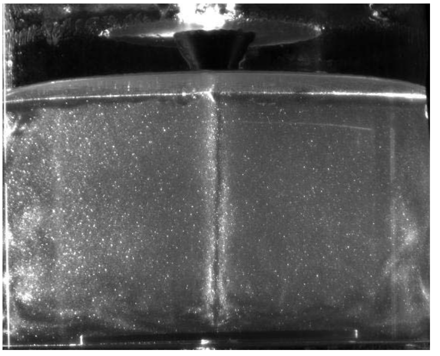


Fig. 3 Visualization photograph of vortex filament under the cone.

3.2. Mass Transfer of Dissolved Oxygen

We perform experiments of oxygen transfer from the air to the water in the test section and measure the dissolved oxygen concentration. The temporal evolution of the dissolved oxygen concentration *Do* can be expressed as

$$\frac{dDo}{dt} = k_L a(Do_s - Do) \tag{1}$$

where k_La and Do_s are a oxygen mass transfer coefficient and a saturation value of the dissolved oxygen concentration. Solving Eq. (1), we obtain the following solution as

$$Do = Do_s - (Do_i - Do_s)\exp(-k_L at) \tag{2}$$

where Do_i is an initial value of the dissolved oxygen concentration. Introducing a shift of time t' where the dissolved oxygen concentration is zero as Do=0, we can rewrite Eq. (1) as

$$Do = Do_s[1 - \exp\{-k_L a(t - t')\}] \tag{3}$$

where the time t' is defined as

$$t' = \frac{1}{k_L a}\ln\left(\frac{Do_s - Do_i}{Do_s}\right) \tag{4}$$

By assuming the form of Eq. (2), the least-square fitting is carried out using Newton-Raphson method and the coefficients of k_La, Do_i and Do_s are calculated from the experimental data. Then, t' can be calculated using the values of the coefficients from Eq. (4). Finally, we can obtain the fitting curve of *Do* for all experimental results where the initial value is zero, i.e. Do_i=0 at t=0, by shifting the time difference of t'.

Under the conditions in our experiments, the mist flow is generated at 1100 rpm when the rotation rate is gradually increased, while the mist flow can be maintained at the lower rotation rate as 800 rpm if the rotation rate is decreased gradually from the situation that the mist flow is already generated at the large rotation rate. Namely, there is a hysteresis for the mist generation depending on the manner of the control of rotation rate. In the case of 1000 rpm, for example, there are two states depending on the manner of the control. One is the state with the mist flow, and the other is that only the circulation exists without the mist flow. Figure 4 is the results of the time evolution of the dissolved oxygen for 1000 rpm. The red solid line shows the time evolution of the dissolved oxygen under the condition with the mist flow, while the blue dashed line under the condition without the mist flow, where the dissolved oxygen is normalized as Do/Do_S using its saturation value. In case without the mist flow, the oxygen transfer is undertaken only due to the circulation formed inside the water under the rotating cone. On the other hand, once the mist flow is generated, the oxygen transfer is enhanced, by a double advantage, due to the circulation and mist flow. As seen in Fig. 4, the elapsed time which is needed to reach its saturation point from zero concentration of the dissolved oxygen is about 25 hours in case without the mist flow, while the time is shorter and about 10 hours in case with the mist flow.

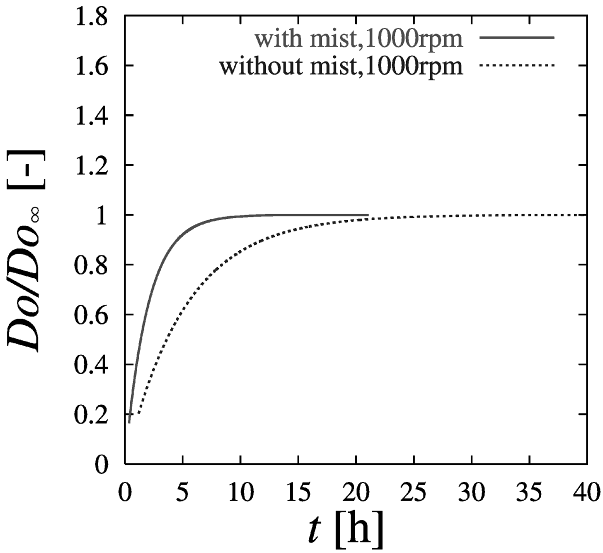


Fig. 4 Dissolved oxygen Do/Do∞ vs. time t

The oxygen transfer is affected by the values of rotation rate because the flow rate of the mist flow and the intensity of the circulation under the cone change depending on the rotation rate. So, we calculate the oxygen mass transfer coefficient $k_L a$ and depict the values in Fig. 5 against the rotation rate ω, where the larger value of the coefficient indicates that the elapsed time to the saturated point is shorter and the oxygen transfer is superior. We can see that the values of the coefficient is smaller for the case without the mist flow and the smaller values continues up to 1200 rpm when the rotation rate is increased from the sufficiently small value. The mist flow is generated when the rotation rate exceeds 1100 rpm, which leads to the increase of the oxygen mass transfer coefficient because the oxygen transfer is enhanced due to the dual effect of the circulation and mist flow. It is evident that the mist flow apparently enhances the oxygen transfer. If the rotation rate is decreased gradually from the situation that the mist flow is already generated, the mist flow is terminated at 800 rpm and the coefficient is decreased abruptly. Therefore, the hysteresis phenomena as mentioned previously can be also seen here.

On the other hand, we can see that the coefficient becomes larger when the rotation rate exceeds 1500 rpm, where a discontinuous increase of the coefficients is observed. This is mainly because the flow pattern inside the test section has changed. That is to say, the flow inside the circular tank is like a free vortex for the smaller rotation rates, while the whole water inside the tank comes to move as a rigid-body rotation and the forced vortex appears for larger rotation rate than 1500 rpm. In such situation with the forced vortex, waves with quite large amplitudes appear on the water surface, which enhance the oxygen transfer.

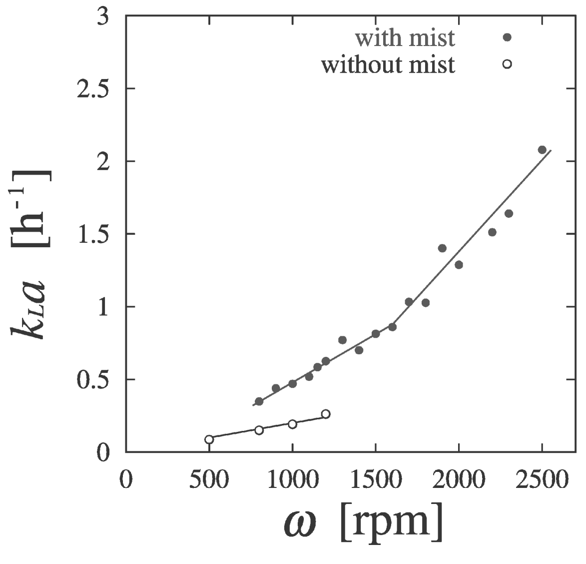


Fig. 5 Oxygen mass transfer coefficients k_La vs. rotation rate ω

4. Conclusions

In this study, we have shown the liquid flow characteristics of the rising film flow along the outer surface of the rotating cone. The film flow goes up along the cone without separating from the cone surface, and is eventually atomized into the mist flow. The mechanism has been used in an oxygen transfer device in order to atomize liquids and generate the mist flow. It should be emphasized that the method is very simple and easier technique to make the mist flow than the existing ones. In addition, we have measured the mass transfer coefficient of the oxygen transfer from the air to the water with the new atomization device for the variations of the rotation rates. Consequently, it is found that the mist flow is quite effective for the oxygen transfer to dissolve the oxygen from the air to the water. We have shown the potential development of the new atomization device using the rotating cone in purification of water quality.

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