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Micro-bubble generation rate and bubble dissolution rate into water by a simple multi-fluid mixer with orifice and porous tube

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ABSTRACT

A multi-fluids mixer by Sadatomi and Kawahara [1] is described as well as its performance as a micro-bubble generator for several trial products. In the experiments, air micro-bubble generation rate at water depths up to 3.6 m and the dissolution rates of oxygen in air and carbon dioxide into tap water at 20 °C were measured. In the analyses, the micro-bubble generation rate data could be well predicted by Sadatomi et al.'s model [2] by choosing suitable energy loss coefficients needed in the model, and the oxygen dissolution rates in tap water could be well correlated with Kawahara et al.'s model [3]. The detail of the multi-fluid mixer and its practical significances together with a result of experiments and analyses are reported in the present paper.

1. Introduction

Micro-bubbles are tiny bubbles, less than a few hundred micrometers in diameter, and have several characteristics, such as high dissolubility in water around them. The most famous application of them is enriching oxygen into water in fisheries of oysters, pearl oysters and so on. Ohnari [4–6] reported that the enrichment promotes the oxygen consumption by the oysters etc. and their blood circulation and metabolism, resulting in the speed-up of their growth. Other applications of the micro-bubbles in industries and several micro-bubble generation methods are described in some books, say by Ueyama and Miyamoto [7].

Sadatomi [8,9] invented a micro-bubble generator (MBG for short) with a spherical body in a flowing liquid tube and with a lot of drilled small holes on the tube for gas suction, in which micro-bubbles could be generated by supplying liquid alone because gas was automatically sucked by a negative pressure arisen behind the body. After that, Sadatomi et al. [2] proposed a model which can predict well the air micro-bubble generation rate by the MBG placed at any water depth, and Kawahara et al. [3] proposed a model which can predict well the dissolution rate of oxygen in air micro-bubbles into water and seawater. However, the MBG has two defects of (a) the difficulty of fixing the spherical body especially in smaller generator and (b) the troublesome drilling of a lot of small holes.

Recently, in order to overcome the above defects, Sadatomi and Kawahara [1] invented a new device with an orifice and a porous pipe instead of the spherical body and the small drilled holes. The new device is called a multi-fluids mixer in our laboratory because of multifunctional, which can generate (a) micro-bubbles by supplying liquid and sucking gas, (b) mists (i.e., tiny liquid droplets) by supplying gas and sucking liquid, and emulsion of immiscible liquids by supplying one of the liquids.

In the present paper, the structure of the multi-fluids mixer and its performance as a MBG are described for several trial products. In the experiments, three kinds of test were conducted: (a) hydraulic performance test of the present MBG, (b) bubble diameter measurement and (c) micro-bubbles dissolution performance test. In (a), air micro-bubble generation rate was measured at water depths up to 3.6 m by changing water supply rate to the MBG systematically. In (b) and (c), bubble diameter and the dissolution rate of oxygen into water through air micro-bubbles in 1.2 m deep water tank at 20 °C and at atmospheric pressure were measured by changing both water supply rate and air suction rate systematically. In (c), the dissolution rate of carbon dioxide into water through carbon dioxide micro-bubbles was also measured. In the analyses, Sadatomi et al.'s model [2] is tested against the present micro-bubble generation rate data by choosing suitable energy loss coefficients needed in the model and Kawahara et al.'s model [3] is tested against the present dissolution rate data of oxygen in air bubbles. A result of such experiments and analyses together with

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Nomenclature

A_H	total area of gas suction hole in porous pipe (m^2)
C	concentration ($kg\ m^{-3}$)
D_L	liquid-phase molecular diffusion coefficient ($m^2\ s^{-1}$)
d	diameter of MBG pipe (m)
d_{BM}	mean bubble diameter (m)
d_{BS}	Sauter mean bubble diameter (m)
d_G	diameter of gas suction hole in porous pipe (m)
d_o	orifice diameter (m)
E_A	ratio of oxygen dissolved into water to that supplied (dimensionless)
E_O	Eotvos number (dimensionless)
f_C	correction factor (dimensionless)
H	water depth (m)
h_G	thickness of porous pipe (m)
h_p	height of bubble diameter measurement (m)
K_La	volumetric mass transfer coefficient (s^{-1})
L_L	water power (W)
l	length of porous pipe (m)
N_C	oxygen mass transfer rate ($kg\ s^{-1}$)
N	number (dimensionless)
p	gauge pressure (Pa)
Q	volume flow rate ($m^3\ s^{-1}$)

T_L	water temperature (°C)
t	time (s)
u_B	bubble rise velocity ($m\ s^{-1}$)
V	volume (m^3)
v	mean velocity ($m\ s^{-1}$)
W_{O2}	mass flow rate of oxygen supplied to water ($kg\ s^{-1}$)

Greek symbols

β	area ratio of orifice to MBG pipe (dimensionless)
ρ	density ($kg\ m^{-3}$)
ς	energy loss coefficient (dimensionless)

Subscripts

E	section far downstream from the exit
G	gas
H	homogeneous
L	liquid
S	saturation
1	inlet section of MBG
2	contraction section of MBG

the detail of the multi-fluid mixer and its practical significances are reported in the present paper.

2. Experiment

2.1. Micro-bubble generator

Fig. 1 shows the orifice type MBG [1] newly developed for the present experiment. The generator has an orifice in a flowing water tube. When pressurized water is introduced into the generator, the water velocity through the orifice becomes several times of that at the generator exit, thus from the energy conservation principle the pressure at a little downstream of the orifice becomes negative. With the aid of the negative pressure, air is automatically sucked through a porous pipe embedded in the pipe, and the air sucked is broken into a huge number of micro-bubbles by a high shear water flow with strong turbulence. Thus the generator can discharge a water jet with micro-bubbles from the exit.

Table 1 lists the specification of the orifice type MBG tested. The first three, named LP-8.8 to LP-14.6, are large types with the same stainless steel punched porous pipe except for the orifice diameter, d_o, being 8.8, 12.5 and 14.6 mm. The diameter of the circular tube was 22.0 mm; the area ratio of the orifice to the tube, β, was changed from 0.16 to 0.44 in order to study the effects of the area ratio; the length and the thickness of the porous pipe were $l = 8$ mm and $h_G = 0.15$ mm; the diameter of each punched holes was $d_G = 300\ \mu m$, and the total area of the holes was $A_H = 152.7\ mm^2$. The last three, SF-4.0 to LF-12.5, were geometrically similar to LP-12.5, but in order to study the effects of the MBG size the sizes of SF-4.0 and MF-8.4 were around 1/3 and 2/3 of LF-12.5. In addition, SF-4.0 to LF-12.5 had the polyolefin (polypropylene polyethylene) fiber porous pipe with the porosity of $d_G = 25\ \mu m$. The thickness and the length of the fiber porous were $h_G = 1.5$ mm and $l = 3$ to 8 mm depending upon the pipe size.

2.2. Test apparatus and measurement systems

Three kinds of test were conducted: (a) hydraulic performance test, (b) bubble diameter measurement test and (c) micro-bubbles dissolution performance test. Fig. 2 shows the present test apparatus and measurement systems. Two water tanks were used as the test water tank: a small transparent acrylic resin water tank with 2.0 m in height and 0.30 m in diameter, and a large opaque poly-vinyl-chloride water tank with 4.0 m in height and 0.489 m in diameter. Water was circulated with a centrifugal pump from the bottom of the tank to the MBG in the tank via a flow control valve and a calibrated magnetic flow meter for the measurement of water volume flow rate, Q_L. The air suction rate into the MBG, Q_G, was measured with a calibrated mass flow meter. The uncertainties in the measurements of Q_L and Q_G are about 1% and about 3%, respectively.

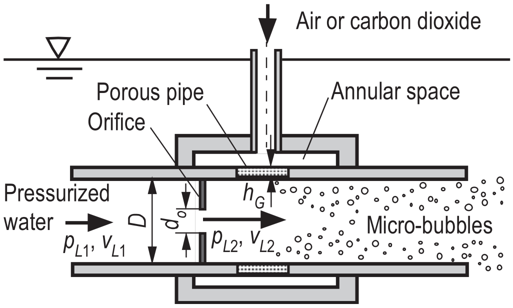

Fig. 1. Micro-bubble generator by Sadatomi and Kawahara [1].

2.3. Hydraulic performance test

In order to familiarize the present MBG to various application fields, the generation rate of the micro-bubbles has to be predictable, depending upon the water depth of MBG placed and water supply rate to the MBG. In addition, a pumping power to supply water to the MBG must be predictable. So, the hydraulic performance test was conducted to obtain experimental data necessary to validate the performance prediction model [2]. In the test, in order to study the effects of water depth of the MBG in the water tank, H, H was changed as 0.4, 0.8, 1.2 m in the small water tank and 2.4 and 3.6 m in the large water tank, and the needle valve