Mass Transfer of Oxygen and Power Consumption with Highly Viscous Liquid in Gas-Liquid Agitated Vessel

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Abstract: The gas-liquid mass transfer volumetric coefficient (K_La) and power consumption under aeration are important parameters for designing gas-liquid agitated vessel. In this work, K_La was calculated by measuring the dissolved oxygen concentration and the mixing power consumption was calculated by measuring shaft torque in the aerated mixing vessel equipped with several types of large paddle impeller. It was found that the aerated mixing power consumption with the large paddle impellers did not decrease largely, because the large cavity was not formed behind the impeller blade. Then, K_La of large paddle impellers used was correlated with a modified equation of Sato *et al.* The intercept of Sato's equation was correlated with the viscosity of CMC aqueous solution. K_La of large paddle impellers is estimated by using the modified Sato's equation over a wide range of viscosity.

Keywords: Mixing, aeration, oxygen absorption, large paddle impeller.

1. INTRODUCTION

There are many publications of the operating characteristics for gas-liquid mixing vessels. The major problem is the decrease of the mixing power consumption under aeration with the Rushton turbine which is used as the standard impeller for gas-liquid mixing [1, 2]. The gas-liquid mixing is conducted when mixing is rate controlling step. Therefore, there are many correlations of the gas-liquid mass transfer volumetric coefficient (K_La) based on the power consumption per unit volume without considering bubble behavior. Most publications referred to the Rushton turbine, because the Rushton turbine was used as the standard impeller in gas-liquid mixing up to now. In recent years, many large paddle impellers that do not have a disk for holding bubbles from the vessel bottom, were developed by Japanese companies, such as Maxblend (MB), Fullzone (FZ), Supermix MR205 (MR205), Sammeler (SM), Hi-F mixer (HiF) and Homebase type impeller (HB). Some publications for the large paddle impeller have reported about the gas absorption from the liquid free surface for gas-liquid mixing [3], and Dohi *et al*. [4] have reported about the aerated mixing. Takahashi *et al*. [5, 6] and Authors [7] showed that the large paddle impeller did not largely decrease the power consumption under aeration. Aida and Shono [8] proposed the correlation of power consumption under aeration.

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Kamei *et al*. [9] showed that a ring sparger whose diameter was larger than the impeller diameter prevented the reduction of the power consumption under aeration and led to the good dispersion of bubbles. This approach was based on the inhibition of the generation of the large cavity formed behind the impeller blade and the prevention of the reduction of the power consumption under aeration. The gas-liquid mass transfer volumetric coefficient (K_La) measured in this approach was correlated with the equation of Sato *et al*. [10]:

$$K_La = 1.8\times10^{-4}\{P_{av}(1/3P_{av}+P_{gv})\}^{0.5} \quad (1)$$

where P_{av} (=$\rho gHQ/V$), P_{gv}, ρ, g, H, Q and V are the aeration power consumption per unit volume, the mixing power consumption per unit volume under aeration, the liquid density, the gravitational acceleration, the liquid depth, the gas flow rate and the liquid volume, respectively.

In our previous paper [7], authors showed that Eq. (1) was valid in air-water system with the large paddle impeller, Eq.(1) was not valid in air-CMC aq. system. However, the correlation of Hiraoka *et al.* [11] was valid in air-CMC aq. system without laminar region. The correlation of Hiraoka *et al.* [11] with the viscosity term is Eq. (2).

$$K_La = (K_La)_a+(K_La)_g \quad (2)$$

$$(K_La)_a = 0.039P_{av}\mu^{-1/3}\sigma^{-2/3}D_L^{1/2}$$

$$(K_La)_g = 0.12P_{av}^{0.12}P_{gv}^{0.70}\mu^{-0.25}\sigma^{-0.6}D_L^{0.5}$$

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where $(K_La)_a$, $(K_La)_g$, μ, σ and D_L are the mass transfer volumetric coefficient by aeration, the mass transfer volumetric coefficient by aerated mixing, the liquid viscosity, the surface tension and the diffusivity of oxygen in liquid, respectively.

In the present work, other various large paddle impellers which had the good mixing performance were used in the gas-liquid mixing vessel, and the effects of these impellers on the power consumption under aeration and K_La were measured and K_La were correlated with a modified equation of Sato *et al*.

2. EXPERIMENTAL

Figures **1** and **2** show the dimensions of the mixing vessel and the large paddle impellers used in this work, where b, B_W, d, and D are the height of impeller blade, the baffle width, the impeller diameter, and the vessel diameter (0.185m), respectively. The mixing vessel was the 10% dished bottom cylindrical vessel made of

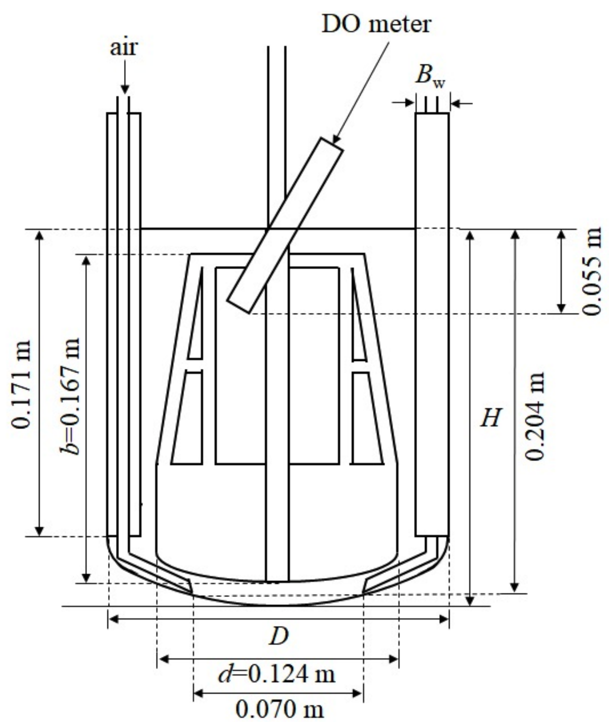

Figure 1: Schematic diagram of experimental apparatus with Maxblend (MB).

acrylic resin. The baffle width B_W was equal to 10% of the vessel diameter (0.019m), and baffles were attached to the vessel wall. The mixing fluids were the deionized water(ρ=999 kg/m^3, μ=1.0 mPa·s) and the carboxymethyl-cellulose (CMC) aqueous solution as highly viscous fluid. These viscosities were measured with viscometer(HAAKE VT 550). CMC 0.2wt% aq. solution (ρ=999 kg/m^3) and CMC 1.2wt% aq. solution (ρ=1005 kg/m^3) were Newtonian fluids and CMC 2.4wt% aq. solution (ρ=1008 kg/m^3) was shear thinning

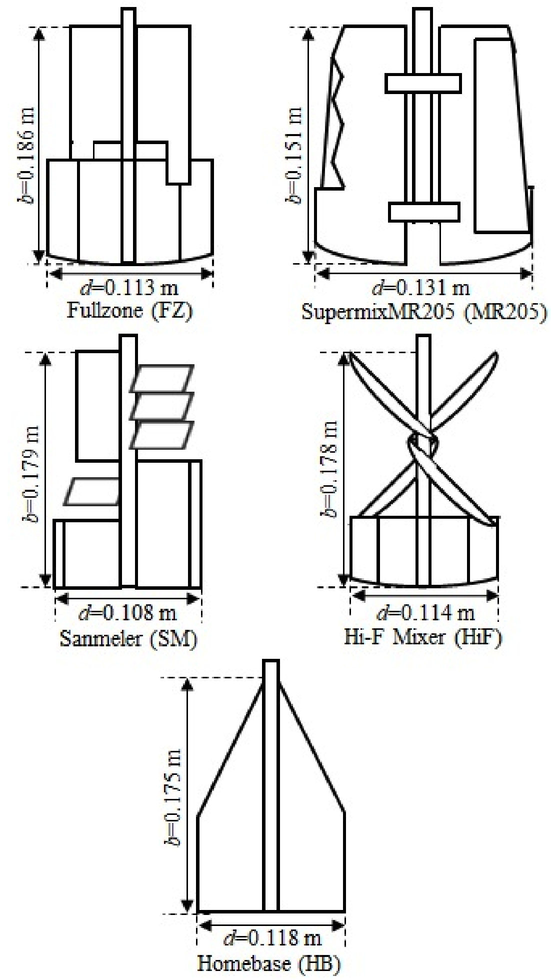

Figure 2: Large paddle impellers.

fluid shown in Figure **3**. As shown in Table **1**, the diffusivity of the oxygen in CMC aq. solution was

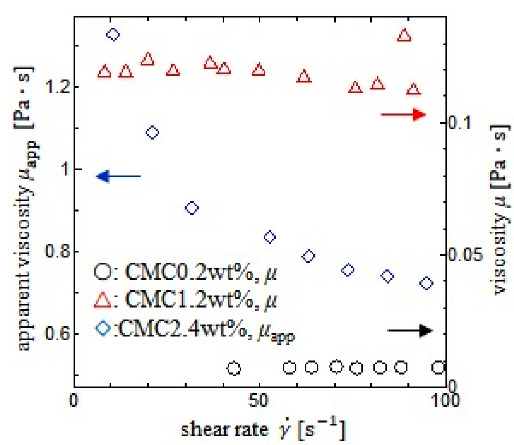

Figure 3: Rheological property of CMC aqueous solutions.

approximately equal to that in water [12, 13]. This is the very important physical property. *H* was 1.1 times of the vessel diameter (0.204m). Two sparger pipes were set at the vessel wall, the external diameter of the sparger pipe was 8mm and the internal diameter was 6mm. The power consumption was measured by the shaft torque measurement method with the torque meter (ST-3000, SATAKE Ltd.). Dissolved oxygen concentration was measured with the optical dissolved oxygen meter (VISIFERM DO ARC 120, HAMILTON). K_La was calculated the DO concentration by previous work [14].

Table 1: Physical Properties of Water and CMC aq. Solution

Liquids	ρ	μ	σ	D_L*
	[kg/m^3]	[mPa·s]	[N/m]	[m^2/s]
Water	996	0.802	0.071	2.60×10^{-9}
CMC 0.2wt%	996	5.90	0.071	2.55×10^{-9}
CMC 0.5wt%	998	12.7	0.070	2.50×10^{-9}
CMC 1.0wt%	1000	46.9	0.069	2.47×10^{-9}
CMC 1.5wt%	1002	119.0	0.069	2.42×10^{-9}

*Nishikawa *et al.* [12]

3. RESULTS AND DISCUSSION

3.1. Power Consumption under Aeration

Figure **4** shows the effect of aeration on power consumption for MB, FZ, MR205, HB, SM and HiF in air-water system (n=250rpm, n_B=2), where n, n_B, N_A (=Q/nd^3), P_0 and P_g are the impeller rotational speed, the number of baffle, the aeration number, the power

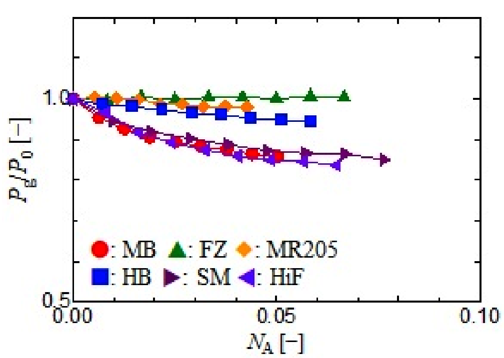

Figure 4: Effect of aeration on power consumption in air-water system.

consumption under no aeration and the power consumption under aeration, respectively. P_0 of MB, FZ, MR205, HB, SM and HiF were 5.4, 4.0, 8.6, 5.1, 3.3 and 3.4W, respectively. P_g/P_0 decreased as N_A increased. The reduction of P_g/P_0 was about 0.85 at the maximum and that was small compared with Rushton turbine. Because the large paddle impellers were operated under low rotational speed, the large cavity behind the impeller wasn't formed [7].

Figure **5** shows the effect of aeration on power consumption for MB, FZ, MR205, HB, SM and HiF in air-CMC 0.2wt% aq. system (n=250rpm, n_B=2, μ=7.5mPa·s). P_0 of MB, FZ, MR205, HB, SM and HiF were 5.5, 3.9, 8.4, 5.1, 3.3 and 3.5W, respectively. P_g/P_0 decreased as N_A increased. The reduction of P_g/P_0 was about 0.85 at the maximum.

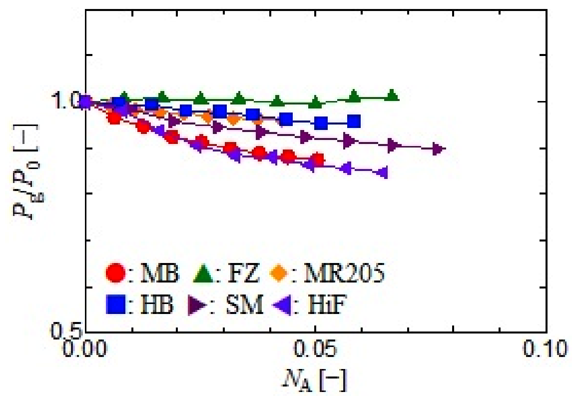

Figure 5: Effect of aeration on power consumption in air-CMC 0.2wt% aq. system.

Figure **6** shows the effect of aeration on power consumption for MB, FZ, MR205, HB, SM and HiF in air-CMC 2.4wt% aq. system (n=250rpm, n_B=0). P_0 of MB, FZ, MR205, HB, SM and HiF were 6.9, 5.5, 9.4, 5.9, 4.7 and 5.7W, respectively. The apparent liquid viscosity μ_{app} of MB, FZ, MR205, HB, SM and HiF were 0.46, 0.55, 0.78, 0.41, 0.64 and 0.72Pa·s, respectively. μ_{app} were estimated with the method of Metzner and Otto [15]. P_g/P_0 decreased as N_A increased. The reduction of P_g/P_0 was about 0.9 at the maximum.

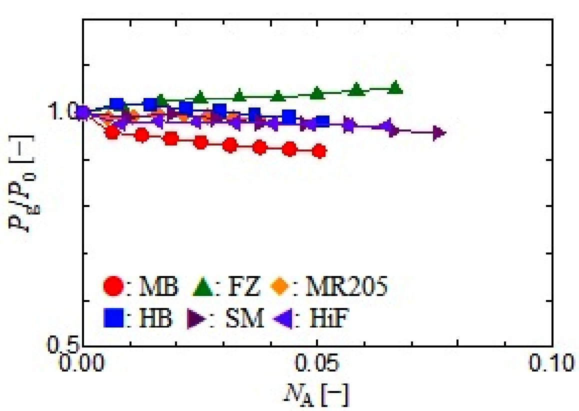

Figure 6: Effect of aeration on power consumption in air-CMC 2.4wt% aq. system.

From the results shown in Figures **5** and **6**, it was found that the large paddle impellers did not largely decrease the aerated power consumption, because the large cavity was not formed behind the impeller blade and the size of that cavity did not increase with viscosity in highly viscous liquid in spite of the gas flow rate [16]. Moreover, the behavior of P_g/P_0 without baffle was the same as the behavior of that with baffle under each viscosity.

3.2 Gas-Liquid Mass Transfer Volumetric Coefficient (K_La)

Figure **7** shows the correlation between K_La and the aerated mixing power consumption for various large paddle impellers in air-water system (n_B=2), where the solid line is Eq.(1). In this case, Eq.(1) was valid in air-water system and the intercept C of Eq.(1) was equal to 1.8×10^{-4} m^3·J^{-1}.

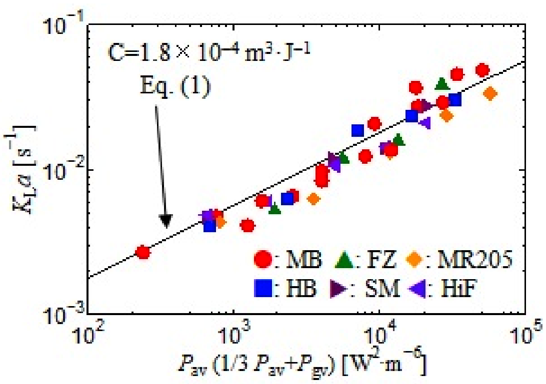

Figure 7: Correlation of K_La in air-water system.

Figure **8** shows the correlation between K_La and the aerated mixing power consumption for various large paddle impellers in air-CMC 0.2wt% aq. system (n_B=2), where the dotted line is Eq. (1). In this case, K_La in CMC 0.2wt% aq. system were slightly lower than those in air-water system. However, the slope of the correlation line was the same as Eq.(1) when C was equal to 1.2×10^{-4} m^3·J^{-1} as shown by the red solid line.

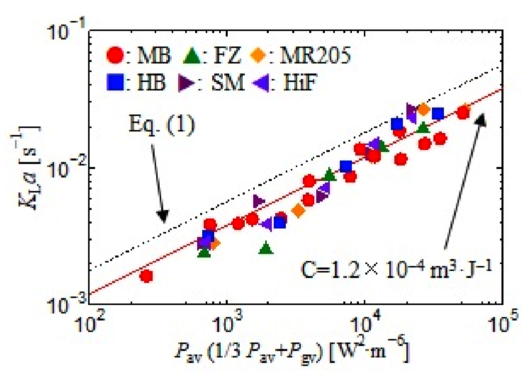

Figure 8: Correlation of K_La in air-CMC 0.2wt% aq. system (7.5 mPa·s).

Figure **9** shows the correlation between K_La and the aerated mixing power consumption for various large paddle impellers in air-CMC 2.4wt% aq. system (n_B=0), where the dotted line is Eq.(1). In this case, K_La in CMC 2.4wt% aq. system were quite lower than those in air-water system and C was equal to 1.5×10^{-5} m^3·J^{-1} (red solid line).

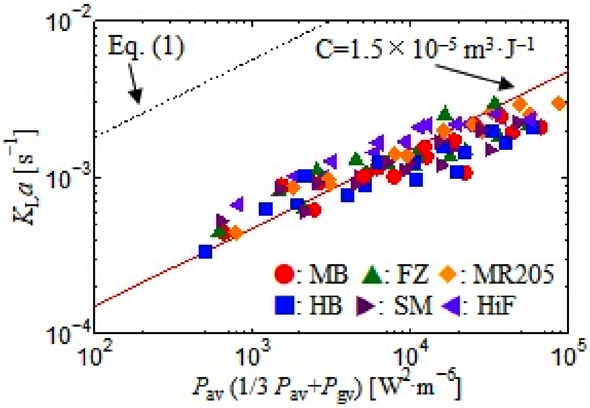

Figure 9: Correlation of K_La in air-CMC 2.4wt% aq. system.

It was considered that the reduction of K_La shown in Figures **8** and **9** was caused by increase of the liquid phase film thickness with viscosity. k_L decreased due to increase of film thickness and that decrease of k_L was larger than the variety of a. As a result, K_La was decreased.

Otherwise, it was considered that because the slope of the correlation lines was the same as shown in Figures **6**, **7** and **8**, the same equation will be used to correlate the mass transfer volumetric coefficient by using modified C. The intercept C in Eq. (1) was modified with the viscosity of CMC aq. solution, because K_La was influenced by the viscosity shown in Figures **8** and **9**. The intercept C can be correlated with following Eq. (3).

$$C = 1.2\times10^{-5}\mu^{-0.41} \quad (3)$$

where μ is liquid viscosity μ or apparent viscosity μ_{app}. The result was shown in Figure **10**. The plots of the viscosity from 0.40 to 0.70 Pa·s were μ_{app} which was calculated for each impeller. By using Eq.(3), the modified Eq.(1) was shown as follows:

$$K_La = 1.2\times10^{-5}\mu^{-0.41}\{P_{av}(1/3P_{av}+P_{gv})\}^{0.5} \quad (4)$$

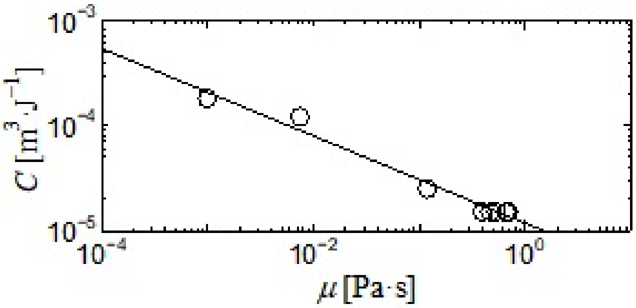

Figure 10: Correlation of constant of Eq. (1) with viscosity.

Figure **11** shows the correlation between K_La calculated with Eq. (4) and K_La observed with various large paddle impellers in air-water and air-CMC aq. system. K_La were correlated with Eq. (4) for all systems in spite of the kind of large paddle impeller.

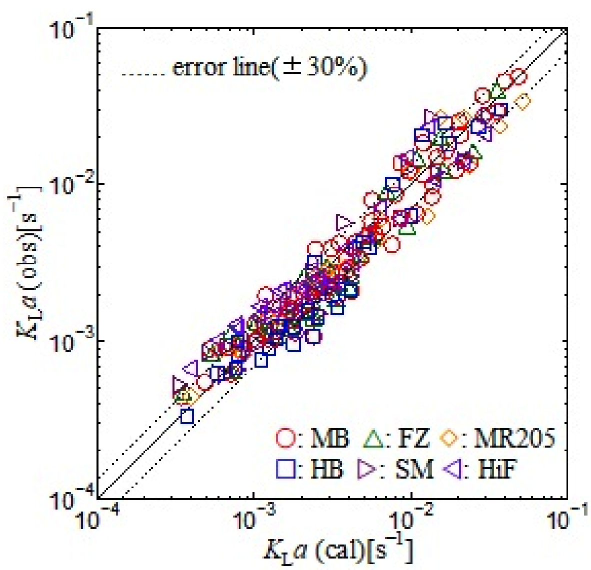

Figure 11: Correlation of K_La in air-water and air-CMC aq. system.

4. CONCLUSIONS

The aerated power consumption and K_La in gas-liquid mixing vessel with various large paddle impellers were measured experimentally using several viscosity liquids. The large paddle impellers did not largely decrease the aerated mixing power consumption as well as the concave turbine. Further investigation needs to understand the difference of the behavior of the P_g/P_0 in each impeller. K_La in air-water, air-CMC 0.2wt% aq. and air-CMC 2.4wt% aq. system with various large paddle impellers were roughly correlated with the modified equation of Sato *et al*. that the intercept was correlated with the viscosity of CMC aq. solution.

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