Nomenclature

E	= thermal efficiency of liquid pump	[—]
E'	= thermal efficiency of closed Rankine cycle	[—]
g	= acceleration of gravity	[m/s ²]
h	= height	[m]
i	= enthalpy	[J/kg]
m	= liquid mass	[kg]
P	= pressure	[Pa]
Q	= heat	[J]
T	= temperature	[K]

V	= balloon volume	[m ³]
W	= work	[J]
ρ_L	= density of liquid lifted	[kg/m ³]
ρ_{v1}	= density of working fluid vapor at point ① in P - i diagram of Fig. 3	[kg/m ³]

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GAS ABSORPTION IN AN AERATED MIXING VESSEL WITH MULTI-STAGE IMPELLERS

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Key Words: Aerated Mixing Vessel, Gas Absorption, Two-Region Model, Multistage Impellers, Turbine, Paddle

Aerated mixing vessels with multistage impellers are often used in the biological and chemical industries. In many cases, k_La has been used as the scale-up standard as reported by Fukuda *et al.*¹⁾ and Tuffile and Pinho,⁶⁾ though the correlative equations for k_La in the literature are limited and, very often, contradictory. Nishikawa *et al.*²⁻⁴⁾ have proposed a dimensionless equation to estimate k_La for a wide range of operational conditions by using the two-region model where the coexistence of the bubbling-controlling condition region and the agitation-controlling condition region in an aerated mixing vessel is assumed.

k_La in an aerated mixing vessel with multistage impellers is discussed in this paper in relation to the two-region model.

1. Experimental

k_La was measured by tracing the change of dissolved oxygen concentration in sugar solutions with time, using an oxygen electrode. Details of the experimental procedures were shown in previous papers by the present authors.^{2,3)}

Physical properties of sugar solutions used in this study are listed in Table 1.

2. Results and Discussion

The dimensionless equation for k_La in an aerated mixing vessel with a turbine-type impeller is shown as follows, using the two-region model.³⁾

$$\begin{aligned} (k_LaD^2/D_L) &= 0.115(d^2n\rho/\mu)^{1.5}(\mu/\rho D_L)^{0.5}(\mu u_g/\sigma)^{0.5} \\ &\quad \times (dn^2/g)^{0.367}(nd/u_g)^{0.167}(d/D)^{0.4}N_p^{0.8} \\ &\quad + 0.112P_{av}/(P_{gv}/N_p + P_{av})(u_g/\sqrt{gD}) \\ &\quad \times (\mu/\rho D_L)^{0.5}(gD^2\rho/\sigma)^{0.66}(gD^3\rho^2/\mu^2)^{0.42} \end{aligned} \quad (1)$$

where P_{gv} and P_{av} are agitation power per unit mass of liquid and aeration power per unit mass of liquid, respectively. (Exponent of -2 for the (d/D) term in Eqs. (13) and (28) in the previous paper³⁾ is incorrect.)

Effects of impeller clearance on k_La for two-stage impellers are compared with the estimated values in Table 2, where agitation power is obtained from the

Table 1. Physical properties of sugar solutions

	10% sol.	30% sol.	50% sol.
ρ [g/cm ³]	1.04	1.13	1.20
σ [g/cm ²]	71	71	71
D_L [cm ² /s]	1.1×10^{-5}	1.2×10^{-5}	3.0×10^{-6}
μ [g/cm ² ·s]	0.015	0.025	0.18

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Table 2. Effect of impeller clearance on $k_L a$ ($D=30$ cm, $H/D=2$, $d/D=1/2$, $b/D=0.1$, $n_p=6$, $n_B=4$, $n=4.17$ s $^{-1}$, $u_g=1.3$ cm/s, 30% sugar solution)

c_1	c_2	Turbine-type		Paddle-type	
		$(k_L a)_{obs}$	$(k_L a)_{cal}$	$(k_L a)_{obs}$	$(k_L a)_{cal}$
10 cm	50 cm	0.0122 s $^{-1}$	0.0118 s $^{-1}$	0.0131 s $^{-1}$	0.0135 s $^{-1}$
10	40	0.0127	0.0134	0.0138	0.0146
10	22		0.0110		0.0118
10	17.5	0.0103	0.0095	0.0115	0.0124
10	15		0.0080		0.0138
10	—	0.0071	0.0072	0.0083	0.0087

correlation reported by Nishikawa *et al.*⁵⁾ As can be seen from this table, the two-region model can be applied to multistage impellers because the estimated values show good agreement with the observed values. A similar conclusion can also be obtained from Fig. 1, where observed $k_L a$ values are compared with estimated values from Eq. (1) for cases when impeller speeds are changed.

Change of impeller power with impeller clearance will have the effect on $k_L a$ shown in Fig. 2, where change of $k_L a$ with impeller clearance under the agitation-controlling condition is estimated for turbine and paddle-type impellers. This figure indicates that addition of the second turbine can increase $k_L a$ by 74% at most, though no increase is expected if the second turbine is not properly positioned.

In the case of a paddle-type impeller, 68% increase can be expected by addition of the second impeller, though improper positioning gives only a 37% increase. It was reported by the present authors³⁾ that the paddle-type impeller gives larger $k_L a$ than the turbine at higher liquid viscosity or smaller P_{gv} . A report by Yagi and Yoshida⁷⁾ implies that the paddle may be better for liquids with large elasticity. Figure 2 also implies that the multistage paddle could be better when there is insufficient impeller clearance.

The present authors recommend the following impeller clearance from the viewpoint of $k_L a$.

$$\Delta c/d > 1.5 \quad \text{for turbine-type} \quad (2)$$

$$\Delta c/d > 1.6 \text{ or } \Delta c/d < 0.1 \quad \text{for paddle-type} \quad (3)$$

The effect of impeller clearance on $k_L a$ becomes smaller with decrease of agitation power, P_{gv} , as is evaluated in Fig. 3, because the bubbling-controlling condition part in the aerated mixing vessel increases. Accordingly, arguments about impeller configurations are meaningless when the vessel condition is bubbling-controlling.

Conclusion

1) $k_L a$ in a mixing vessel with multistage impellers can also be correlated by the expression for a vessel

Fig. 1. Comparison of observed $k_L a$ with estimated values for aerated vessel with multistage impellers.

Fig. 2. Effect of clearance on $k_L a$ under agitation-controlling condition.

Fig. 3. Effect of clearance when aeration becomes comparatively strong.

with an impeller, using the two-region model.

2) The proper impeller clearance is required to obtain an effective increase of $k_L a$ by addition of a impeller.

Nomenclature

b	= blade width of impeller	[cm]
c	= impeller level from vessel bottom	[cm]
c_1	= first-stage impeller level from vessel bottom	[cm]

c_2	= second-stage impeller level from vessel bottom	[cm]	= surface tension	[g/cm ²]
Δc	= clearance between impellers	[cm]		
D	= vessel diameter	[cm]		
D_L	= liquid-phase diffusivity	[cm ² /s]		
d	= impeller diameter	[cm]		
g	= gravitational acceleration	[cm/s ²]		
H	= liquid height in vessel	[cm]		
$k_L a$	= capacity coefficient in gas absorption	[s ⁻¹]		
$(k_L a)_0$	= $k_L a$ obtained in vessel with single-stage impeller where $H/D=1$	[s ⁻¹]		
N_p	= power number	[—]		
n	= impeller speed	[s ⁻¹]		
n_B	= number of baffle plates	[—]		
n_p	= number of impeller blades	[—]		
P_{av}	= aeration power per unit mass of liquid	[cm ² /s ³]		
P_{gv}	= agitation power per unit mass of liquid	[cm ² /s ³]		
	= liquid viscosity	[g/cm · s]		
	= liquid density	[g/cm ³]		

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SECOND VIRIAL COEFFICIENT OF ETHANE AT 423.15 K AND PREDICTION OF SECOND VIRIAL COEFFICIENTS FOR NORMAL ALKANES

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Key Words: Physical Property, Second Virial Coefficient, Ethane, Normal Alkane, Molecular Potential Model

In a previous paper,⁷⁾ a simple potential model based on a group-contribution concept was proposed for predicting second virial coefficients of linear symmetric molecules. At that time, fundamental group parameters of the methyl group for the model were determined tentatively from literature values of second virial coefficients for ethane.

In the present study, the second virial coefficient of ethane at 423.15 K was measured by the Burnett method. Thereafter, by use of the value at 423.15 K and that at 298.15 K obtained previously,⁴⁾ the group parameters of the methyl group for the model have been redetermined.

1. Second Virial Coefficient of Ethane at 423.15 K

The experimental apparatus and procedures used in the present study were identical to those described in a previous paper.⁶⁾

Research-grade ethane supplied by Phillips

Petroleum Co. had a specified minimum purity of 99.99 mol% and was used without further purification in the experiments.

The method of data reduction based on the virial equation of Berlin-form is the same as that used in a previous paper.⁴⁾

The second virial coefficient of ethane obtained in the present study is compared with literature values in Table 1. The values of Dymond-Smith²⁾ and of Douslin-Harrison¹⁾ are larger than the value obtained in the present study by about 2–3 cm³ · mol⁻¹. The value of Eubank-Mansoorian³⁾ is in good agreement within experimental uncertainty. On the other hand, the prediction result of Tsonopoulos⁸⁾ is smaller by about 2 cm³ · mol⁻¹ in absolute terms.

2. Prediction of Second Virial Coefficients for Normal Alkanes

A simple potential model (abbreviated OK model hereafter), proposed for predicting second virial coefficients of linear symmetric molecules in the previous

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