

Transport Phenomena around Cylindrical Baffles in an Agitated Vessel Measured by an Electrochemical Method

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The mass transfer coefficient of cylindrical baffles in an agitated vessel has been measured for the first time with the constant potential method using aqueous solution of 1N-KOH + 0.2N-K₄Fe(CN)₆ + 0.01N-K₃Fe(CN)₆. The average mass transfer coefficient on the baffles was three to five times larger than that of the vessel wall based on the power consumption per unit volume. The average mass transfer coefficient on the baffles increased with decreasing baffle diameter. The number of baffles, the clearance between the baffles and vessel wall, the position of the baffles and the position of the impeller did not affect the average mass transfer coefficient of the baffles under these experimental conditions. The average mass transfer coefficient of the cylindrical baffles measured herein agrees with the value obtained by an equation based on one published before. The distributions of the local mass transfer coefficient of the cylindrical baffles are shown graphically for various impeller speeds. The local mass transfer coefficient of the baffles near the impeller was larger than those in other positions, and that near the liquid free surface increased up to the same level as that of the baffles near the impeller as the impeller speed increased.

Introduction

Heat transfer in mixing vessels is a very important consideration. Normally, a jacket or a coil is set up to heat or cool the materials in an agitated vessel. The jacket has an advantage with respect to ease of maintenance, but the area of heat transfer is smaller than in the case of the coil. On the other hand, maintenance of the coil is not easy. For example, the length of the coil changes frequently with heating and cooling, and slurry sediment is deposited on the coil. In some actual plants, vertical cylindrical coils are sometimes used as baffles. Kamei *et al.* (2004) reported the power consumption of the agitated vessel with cylindrical baffles.

Heat is transferred through the vessel wall with the jacket or through the coil in an agitated vessel. Many investigators have correlated the heat transfer coefficient on the vessel wall with Nusselt, Reynolds and Prandtl numbers. Carreau *et al.* (1994) reviewed several studies concerning heat transfer to Newtonian and non-Newtonian liquids in screw agitator and draft coil systems. However, few studies have examined the heat transfer coefficient on the coil. In particular, there has been no report regarding vertical tubes or baffles.

Mizushima *et al.* (1969) developed an electrochemical method for measuring the local heat transfer coefficient on the vessel wall using an analogy between heat and mass transfer (Chilton *et al.*, 1934). Kato *et al.* (1995, 2005) reported the distribution of the local heat transfer coefficient on the vessel wall for shaking vessels and for new anchor

impellers as obtained using the electrochemical measurement method.

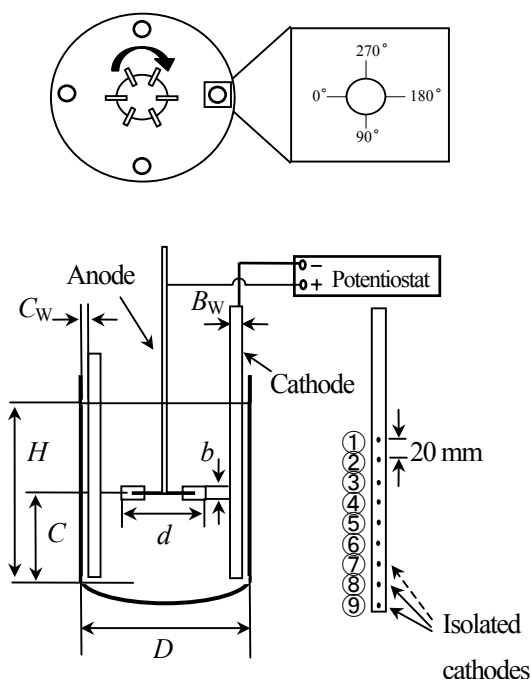
In the present study, vertical cylindrical coils (cylindrical baffles) were employed as baffles in a turbulent agitated vessel with a Rushton turbine. The distribution of the local heat (mass) transfer coefficient on the cylindrical baffles was measured using the electrochemical method.

1. Experimental Method

A schematic diagram of the experimental apparatus is shown in **Figure 1**. The cylindrical vessel was made of nickel-plated brass, and the diameter D of the vessel was 185 mm. The dimensions of the Rushton turbine and the baffles are listed along with the other experimental conditions in **Table 1**.

The mass transfer coefficients of the vessel wall and the cylindrical baffles were measured by the constant potential method using 1N-KOH + 0.2N-K₄Fe(CN)₆ + 0.01N-K₃Fe(CN)₆ (Wako Pure Chemical Industries, Ltd.) aqueous solution. As shown in Figure 1, the vessel wall or baffle was used as the cathode for measuring the average mass transfer coefficient, and nine isolated point cathodes of 1.0 mm in diameter were used to measure the local mass transfer coefficients. The isolated point cathodes were located on the baffles at 20-mm intervals. Baffles of various sizes were used to measure the average mass transfer coefficient. When the local mass transfer coefficients were measured, only the

baffles of 18 mm in diameter were used. The anode was the shaft at the center of the agitated vessel. The limiting electrical current on the cathode was measured using the electrolytic method by constant potential, and the mass transfer coefficient was then estimated using the following equation (Mizushina *et al.*, 1969; Hiraoka *et al.*, 1981; Kato *et al.*, 1995):

**Table 1** Experimental conditions**Table 2** Physical properties of the liquid

A tracer method was used to visualize the flow patterns. Nylon particles with an average diameter of 200 μm moved in the vessel and were illuminated by an Ar-laser slit beam. The particles were photographed with an exposure time of one second.

2.1 Average mass transfer coefficient on cylindrical baffles

$$\bar{k} = 0.13(P_V \mu / \rho^2)^{1/4} Sc^{-2/3} \quad (2)$$



















B_W						n_b
2 mm		5 mm		10 mm		
Wall	Baffles	Wall	Baffles	Wall	Baffles	
						2
						4
						8

Fig. 2 Effect of diameter and number of baffles on mass transfer coefficient

The number of baffles and the clearance between the baffles and the vessel wall did not affect the average mass transfer coefficient on the baffles under these experimental conditions except for the baffle diameter, as shown in **Figure 3**. But \bar{k} decreased with increasing baffle diameter.

Table 3 Comparison of average mass transfer coefficients ($B_W = 10$ mm, $n_b = 4$, $N = 2.5$ s⁻¹)

	with baffles	without baffles
$\bar{k}_{(wall)}$ [m·s ⁻¹]	1.13×10^{-5}	1.35×10^{-5}
$\bar{k}_{(baffle)}$ [m·s ⁻¹]	3.67×10^{-5}	—
$A_{(wall)}$ [m ²]	0.123	0.123
$A_{(baffle)}$ [m ²]	2.14×10^{-2}	—
ΣkA [m ³ ·s ⁻¹]	2.18×10^{-6}	1.67×10^{-6}

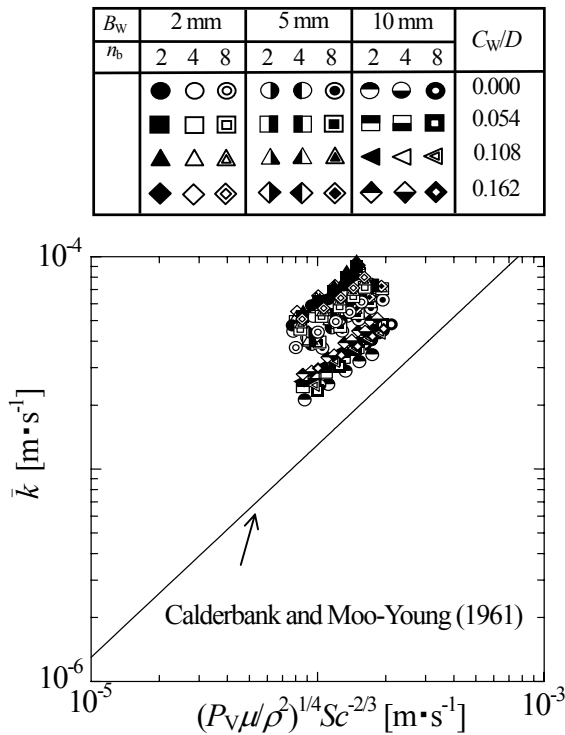


Fig. 3 Effect of clearance between the baffles and the wall on the mass transfer coefficient

2.1.1 Effect of baffle position on average mass transfer coefficient The baffle position did not affect the average mass transfer coefficient on the baffles under these experimental conditions, as shown in **Figure 4**.

The baffles were set up as shown in Figure 4. The outer cylindrical baffles were fixed at a distance of 10 mm from the vessel wall, and the position of inner baffle was varied. The average mass transfer coefficient on the inner baffles was then measured, and was found not to depend on the distance between the baffles.

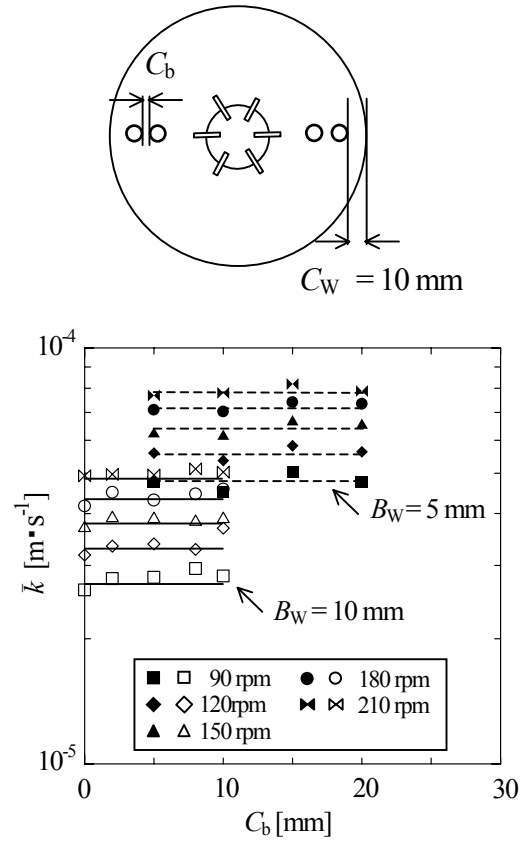


Fig. 4 Effect of the baffle position on k

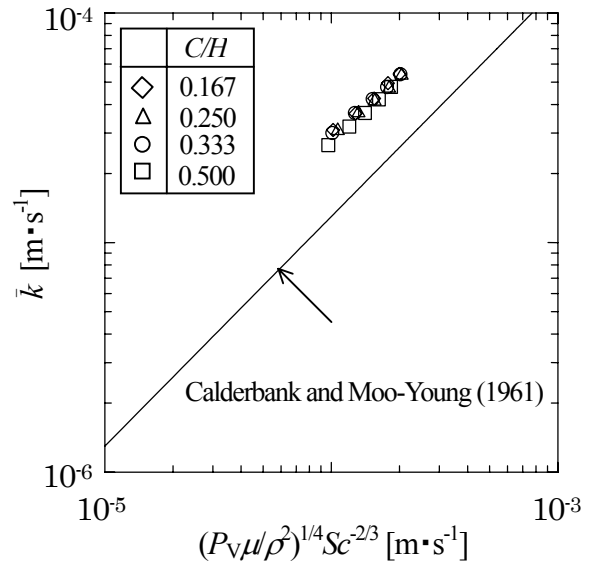


Fig. 5 Effect of the impeller position on k

2.1.2 Effect of impeller position on the average mass transfer coefficient The position of the impeller did not affect the average mass transfer coefficient on the baffles under these experimental conditions, as shown in **Figure 5**. The power consumption and flow pattern with the Rushton turbine were considered not to have changed, regardless of the position of impeller (Kamei *et al.*, 1995).

2.1.3 Correlation of average mass transfer coefficient on baffles Sano *et al.* (1981) proposed the correlation of the heat transfer coefficient on the helical coil in the mixing vessel as follows:

$$Nu = 0.755(\varepsilon d_{co}^4/\nu^3)^{0.19} Pr^{1/3} (d/D)^{0.11} (b/D)^{0.09} \quad (3)$$

where ε is P/ρ , d_{co} is the coil diameter, and $\varepsilon d_{co}^4/\nu^3$ is the Reynolds number based on the turbulent theory. Therefore, Eq. (3) is applied to correlate the average mass transfer coefficient on the cylindrical baffles. Here, Nu and Pr can be substituted for Sh and Sc by analogy. In addition, the coil diameter d_{co} was substituted for the baffle diameter B_w .

$$Sh = 1.55(\varepsilon B_w^4/\nu^3)^{0.19} Sc^{1/3} (d/D)^{0.11} (b/D)^{0.09} \quad (4)$$

In **Figure 6**, the experimentally obtained values are compared with those given by Eq. (4), where the constant 0.755 changed to 1.55. The correlation deviation of experimental data was approximately 25%.

2.2 Local mass transfer coefficient on cylindrical baffles

2.2.1 Distribution of local mass transfer coefficient on cylindrical baffles

The distributions of local mass transfer coefficients on a cylindrical baffles are shown graphically in **Figure 7** for several impeller speeds, N , a baffle diameter of $B_w = 18$ mm, a clearance between the baffles and the vessel wall of $C_w = 15$ mm, and for a number of baffles n_b of 4. Because the radial flow velocity at the impeller position was largest in the agitated vessel, the mass transfer coefficient on the baffles was largest at the surface level, as shown in red in Figure 6. In addition, the mass transfer coefficient in the range between 180 and 360° was larger than in the other regions, because the discharge flow from the impeller directly collided with the baffles. Interestingly, the mass transfer coefficients of the upper and lower parts increased with increasing impeller speed.

B_w	2 mm			5 mm			10 mm			C_w/D
n_b	2	4	8	2	4	8	2	4	8	
	●	○	⊙	●	○	⊙	●	○	⊙	0.000
	■	□	⊠	■	□	⊠	■	□	⊠	0.054
	▲	△	▴	▲	△	▴	▲	△	▴	0.108
	◆	◇	⬠	◆	◇	⬠	◆	◇	⬠	0.162

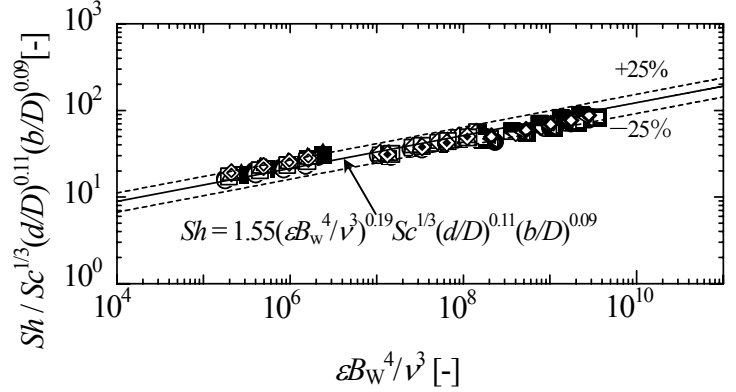


Fig. 6 Correlation of average mass transfer coefficient on cylindrical baffles

The photograph of liquid free surface indicates that the disturbance of the liquid free surface increased with increasing impeller speed. The position of the baffle clamp should be decided based on these results.

2.2.2 Effect of impeller position on local mass transfer coefficient

The average mass transfer coefficient did not vary with the position of the impeller, as shown in Figure 5. The local mass transfer coefficient distribution depends on the position of the impeller, as shown in **Figure 8**, and that close to the impeller was larger than that at other positions, but that close to the liquid free surface decreased with decreasing clearance between the impeller and the vessel bottom. The experimental conditions were the same as shown in Figure 6.

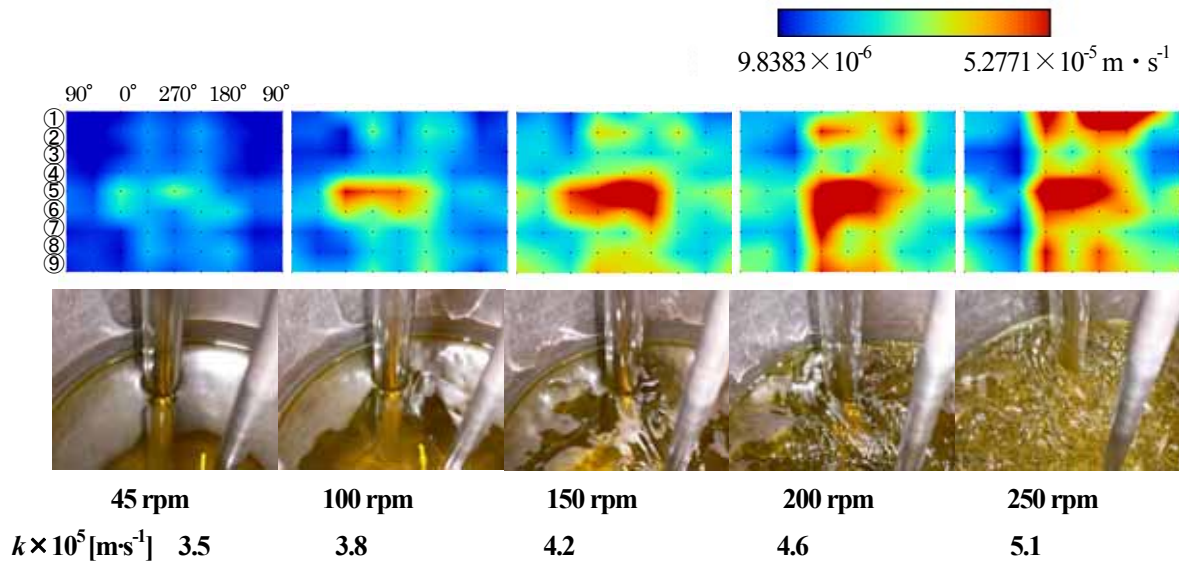


Fig. 7 Distribution of local mass transfer coefficient on cylindrical baffles

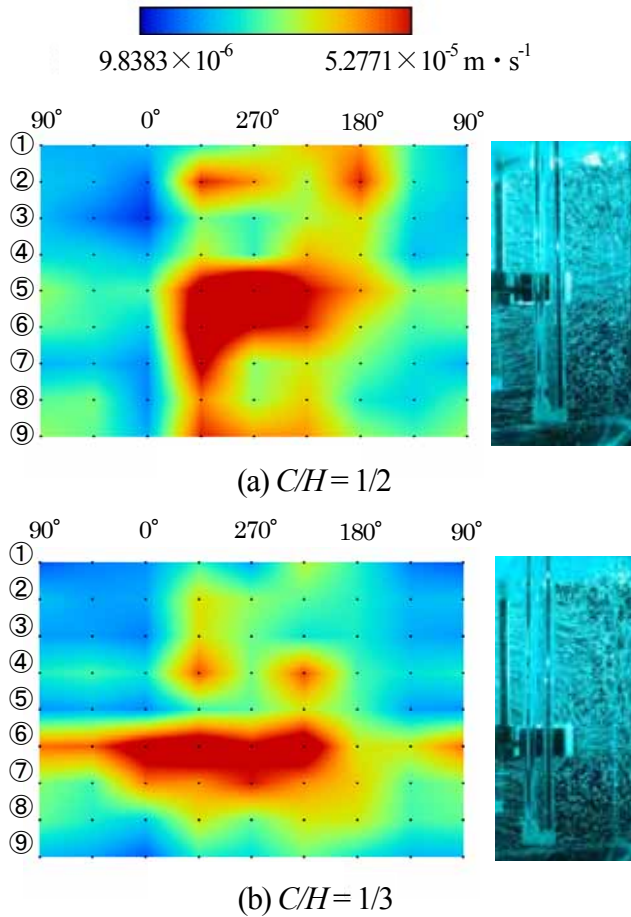


Fig. 8 Distribution of local mass transfer coefficient on cylindrical baffles and flow pattern at 200 rpm

Conclusions

The mass transfer coefficient on the vertical cylindrical baffle was investigated using the electrochemical method. The average mass transfer coefficient on the baffles increased with decreasing baffle diameter.

The number of baffles, the clearance between the baffles and the vessel wall, the position of baffles and the position of the impeller do not affect the average mass transfer coefficient on the baffles under the experimental conditions of the present study. The average mass transfer coefficient on the cylindrical baffles was correlated as described by Sano *et al.* (1981), and the coil diameter was substituted for the baffle diameter.

The distributions of local mass transfer coefficients of cylindrical baffles were shown graphically. The local mass transfer coefficient on the baffle surface near the impeller was larger than that at other positions, but that close to the liquid free surface increased with increasing impeller speed.

Nomenclature

A	= surface area of the cathode	[m ²]
b	= impeller height	[m]
B_W	= diameter of a cylindrical baffle	[m]
C	= clearance of between an impeller and the vessel bottom	[m]
C_b	= clearance between baffles	[m]
C_{ferri}	= bulk concentration of $Fe(CN)_6^{3-}$	[kmol·m ⁻³]
C_W	= clearance between a baffle and the vessel wall	[m]
d	= vessel diameter	[m]
D_{ferri}	= diffusivity of $Fe(CN)_6^{3-}$	[m ² ·s ⁻¹]
D	= impeller diameter	[m]
d_{co}	= helical coil diameter	[m]
F	= Faraday constant ($= 9.65 \times 10^7$)	[C·kmol ⁻¹]
H	= liquid height	[m]
I_d	= limiting electrical current	[A]
k	= local mass transfer coefficient	[m·s ⁻¹]
\bar{k}	= average mass transfer coefficient	[m·s ⁻¹]
N	= impeller rotational speed	[s ⁻¹]
n	= number of electrons involved in the electrode reaction ($=1$)	[-]
n_b	= number of baffle	[-]
Nu	= Nusselt number	[-]
Pr	= Prandtl number	[-]
P_V	= power consumption per unit volume	[W·m ⁻³]
Re	= impeller Reynolds number ($= Nd^2/\nu$)	[-]
Sc	= Schmidt number ($= \nu/D_{ferri}$)	[-]
Sh	= Sherwood number	[-]
ε	= turbulent energy dissipation rate	[W·kg ⁻¹]
μ	= liquid viscosity	[Pa·s]
ρ	= liquid density	[kg·m ⁻³]
ν	= kinematic viscosity of liquid	[m ² ·s ⁻¹]

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