Augmentation Mechanism of Mass Transfer Among Turbulence Promoters on Wall Surface in Rectangular Duct

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ABSTRACT

An augmentation mechanism of mass transfer was investigated phenomenologically by using turbulence promoters on the wall surface in a rectangular duct. The augmentation of local mass transfer among the turbulence promoters was measured by varying the diameter, the pitch of the promoters and the clearance between the promoters and the wall. In order to examine the augmentation mechanism, wall shear stress, mass transfer intensity and turbulence intensity at the wall were measured by an electrochemical method. Further, flow behaviors were measured by visualization.

It was found phenomenologically that the augmentation of mass transfer with the clearance was caused by turbulence due to reattachment flow, large scale eddies and increase of shear stress due to flow jet under the promoters and was caused by only turbulence on the wall surface in case of no clearance.

1. INTRODUCTION

It is well known that roughening the surface by use of turbulence promoters (reqular geometric roughness element) on the wall surface in a duct improves the heat transfer from the surface for the design of compact heat exchanger. The increase in heat transfer is accompanied by an increase in resistance to fluid flow. The problem of optimizing heat transfer performance for given flow friction has been studied by many investigators. Some of them are shown in Table 1.

It has been found in practical applications that an increase in flow resistance does not always decrease energy efficiencies. However, few investigations of the augmentation mechanism of heat transfer have been published.

Mori et al[16] and Fujita et al[4] suggested that augmentation of heat transfer depends mainly on turbulence intensity near the wall surface downstream from a single cylinder turbulence promoter placed on the transfer wall in a reetangular duct.

Miyashita et al[14] pointed out that augmentation depends on the turbulence intensity near the wall surface in the case of no clearance between promoter and wall, and depends not only on the turbulence intensity but also on the shear stress at the wall in the case of non-zero clearances in a rectangular duct.

In this paper, the augmentation ratio of local mass transfer coefficients among the promotres was measured by varying the diameter, the pitch of the promoter and the clearane between promoter and wall surface. Flow behavior was observed by visualization. Wall shear stress, mass transfer intensity at the wall and turbulence intensity close to the wall surface were measured by an electrochemical method, in order to examine the detailed augmentation mechanism of heat/mass transfer on the wall surface among the turulence promoters in a rectangular duct.

INVESTIGATORS	GEOMETRY	PROMOTER	FULUID	EXPERIMENTAL CONDITION
Mori et al.[16]	rectangular duct (H=33mm,W=77mm)	cylinder	electrolyte solution	$Re=4.5\times10^4$,H/Dp=6.6
Kasagi et al.[9]	water tunnel	(step)	water	U_∞=25-60cm/s,step height=10,20,30cm
Igarashi et al.[8]	wind tunnel	(step)	air	U_∞=6-24cm/s, step height=10cm
Fujita et al.[4]	wind tunnel	cylinder	air	U_∞=20cm/s, Dp=5mm
Oyakawa et al.[18]	rectangular duct (H=50mm,W=300mm)	cylinder	air	$Re=2.5\times10^4$,H/Dp=1.25-2.5
Hanawa et al.[6]	rectangular duct (H=10mm,W=50mm)	cylinder	air	$Re=6\times10^3-3\times10^4$, H/Dp=2,P/Dp=5,10, 15,20
Rao et al.[20]	annulus (Do=152mm,Di=76mm)	wire ring	air	$Re=9\times10^4-2.2\times10^5$,(Do-Di)/2Dp=30,42 P/Dp=3,7,10
Furuya et al.[5]	wind tunnel	cylinder	air	U_∞=13,21cm/s,Dp=2mm,P/Dp=1-64
Han etal.[7]	rectangular duct (H=13,25mm,W=301mm)	rectangular rib	air	$Re=3\times10^3-3\times10^4$,H/e=10-30,P/e=5-20
Konno et al.[11]	rectangular duct (H=2.6, 5mm,W=70mm)	cylinder	water	$Re=8\times10^2-3\times10^4$,H/Dp=1.3-3.1,P/Dp= 2-56
Oyakawa et al.[19]	rectangular duct (H=50mm, W=300mm)	cylinder	air	$Re=9\times10^4-1.7\times10^5$,H/Dp=2.5, P/Dp= 4,8,12

Table 1 Investigations on enhanced heat transfer using turbulence promoters

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the experimental apparatus and a detail of the test section are shown in Fig. 1 and Fig. 2, respectively. The dimensions of the cross section in a duct for mass transfer measurements were 40 x 50 mm (height by width). The test section was 2800 mm long (63 hydraulic diameters in length) to obtain the hydraulically fully developed flow at the mass transfer section. Following the entrance region, a mass transfer development region of 10 x90 mm preceded the cathode (10 x 360 mm) for measurement of average mass transfer coefficients. Further, 1.0 mm platinium point electrodes (30 points) for the measurement of the local mass transfer coefficients, wall shear stress and mass transfer intensity were arranged at intervals of 5 mm on the nickel cathode. Two anodes (17 x 450 mm^2) were located on the bottom side of cathode. Each electrode was isolated electrically by epoxy resin. A blunt nose type probe with 0.3 mm platinium wire was used to measure the velocity profile in the duct.

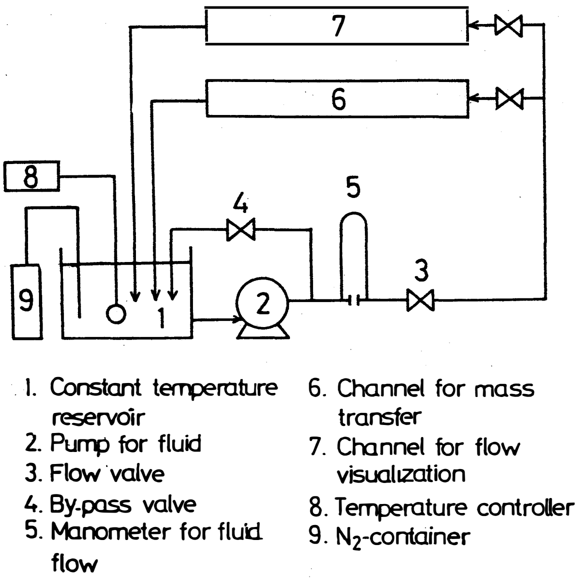


Fig. 1 Schematic diagram of experimental apparatus

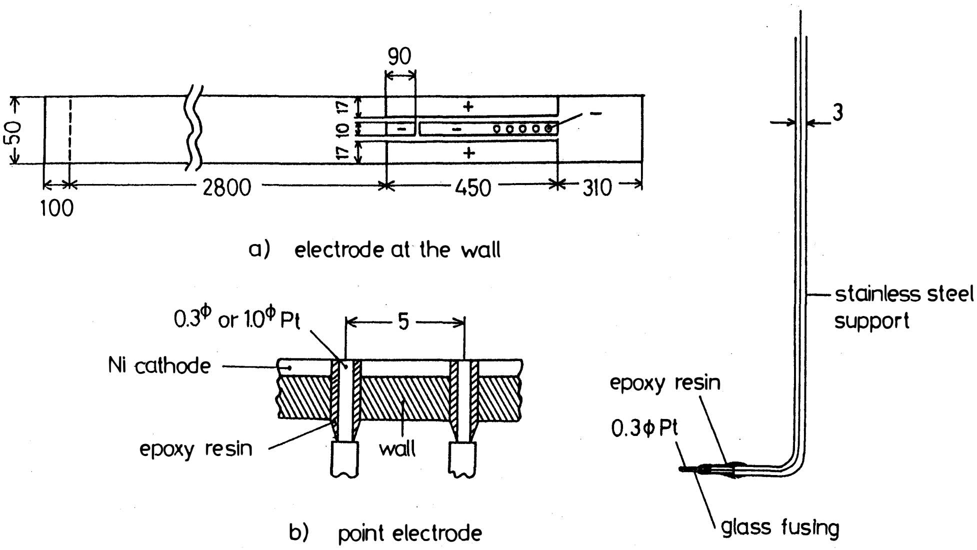


Fig. 2 Details of test section and probe

Experiments were carried out by varying the diameter of turbulence promoters Dp(3,5.7 and 10 mm), clearance between the promoter and the wall surface c (0,1.3,5,7,10 and centre), pitch among the promoters p ($p/Dp=5,7,9,12$ and 16) and flow Reynolds number Re ($6.64 \times 10^3 - 1.73 \times 10^4$).

In experiments for the electrochemical method, 0.005M potassium ferri/ferro cyanide and 2M sodiumhydroxide used as electrolyte solution. Temperature was set up 303 ±0.5 K. The density and viscosity of electrolyte were 1075 kg/m^3 and 0.0013 Pa. s (N. s/m^2) respectively. The diffusion coefficient for the ferricyanide ion was 5.776 x 10^{-10} m^2/s given by Mitchell and Hanratty's correlation[21], and the Schmidt number was equal to 2097.

In experiments for visualization, aluminium powder was suspended in water[1]. The flow pattern was observed in a transparent duct. The experimental conditions were similar to those for the measurement of mass transfer.

The coordinates and variables of the test section are shown in Fig. 3.

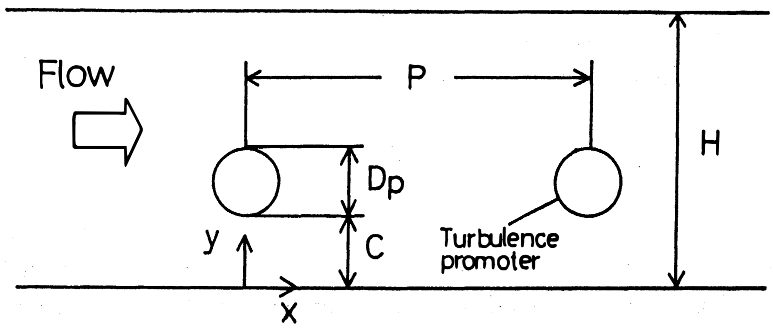


Fig. 3 Coordinates and notations of test section

3. CALCULATIN OF TRANSPORT PHYSICAL FACTORS

The mass transfer coefficients were measured by using the potassium ferri/ferrocyanide redox electrochemical reaction as reviewed in detail by Mizushina[15]. The basis of the method is that when operating at the so-called "limiting current" condition the electrochemical phenomena are limited by mass transfer at the cathode only, and hence the concentration of ferricyanide ion is zero at this electrode. Mass transfer limitations do not occur at the anode, if its transfer area is very large relative to that at the cathode. Under these conditions, the mass transfer coefficient is given by

$$k = \frac{i}{n_e . F . A . C_b} \qquad (1)$$

To overcome ion-migration effects in a potential field, potassium ferricyanide solution is dissolved in strong electrolyte, in this case sodiumhydroxide when the concentration of this unreactive electrolyte is high compared to the concentration of ferricyanide ion, the transfer of ferricyanide ion is done ordinary diffusion or by the ordinary mass transfer mechanism with constant composition at the wall.

The principle of the shear stress and the fluid velocity measurement is also described by Mizushina [15]. The wall shear stress on the bottom wall can be calculated from following the equation in the case of circular surface.

$$\tau = 3.55 \times 10^{-15} \frac{\mu . i}{D^2 . C_b^3 . d^5} \qquad (2)$$

The above equation is given by the solution of Leveque, assuming that the velocity profile is linear and that the Prandtl number of the fluid is large.

The fluid velocity can be calculated by the following equation from limiting current measured by a blant nose type probe.

$$\mu = (i - \alpha)^2 / \beta^2 \qquad (3)$$

where, α and β are constants given by calibration.

Mass transfer intensity is defined by the following equation.

$$I = 100 \frac{\sqrt{\overline{k'^2}}}{k_0} \qquad (4)$$

ko and k' is calculated from Eq. (1), where $\sqrt{\overline{k'^2}}$ is the root mean square value for the fluctuating component of mass transfer coefficient. k_0 is the time averaged mass transfer coefficient in a smooth duct. Mass transfer intensity is a transport property to be obtained the information on turbulence close to the wall surface. Electric circuits for the measurements of mass transfer coefficient, the intensity, and fluid velocity using a probe are shown in Fig. 4.

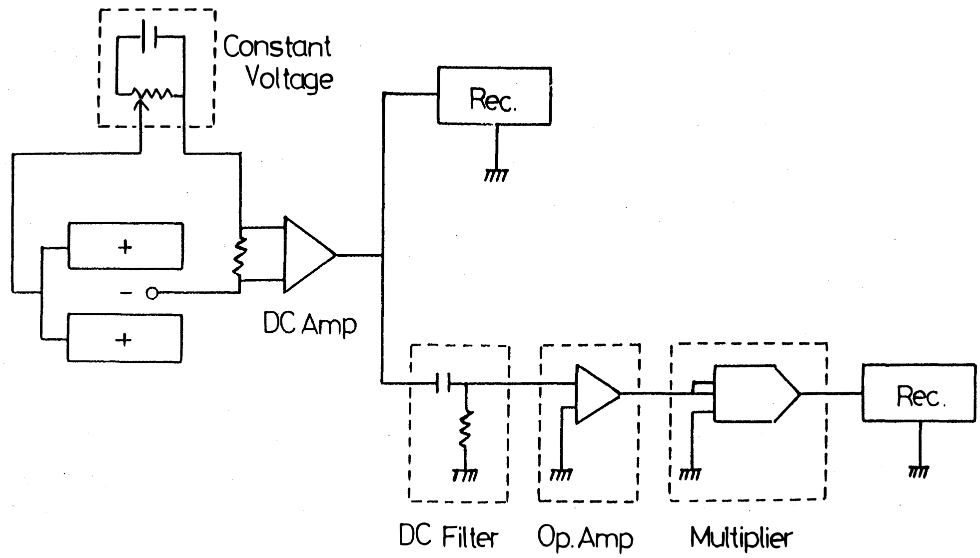


Fig. 4 Electric circuits for measurement of transport factors

4. EXPERIMENTAL RESULTS AND DISCUSSIN

pre-experiment

Before initiating experiments with turbulence promoter, mass transfer coefficient, friction factor and velocity profile were measured for smooth duct as shown in Fig. 5, 6 and 7, and obtained the following correlations, respectively.

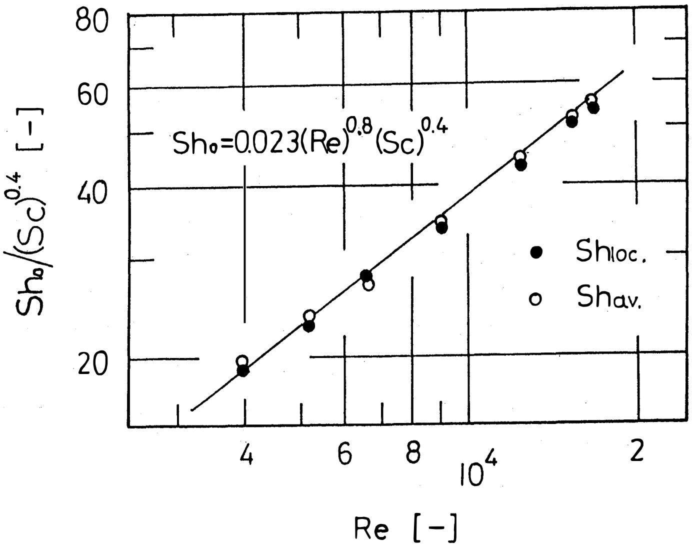


Fig. 5 Mass transfer coefficient for smooth duct

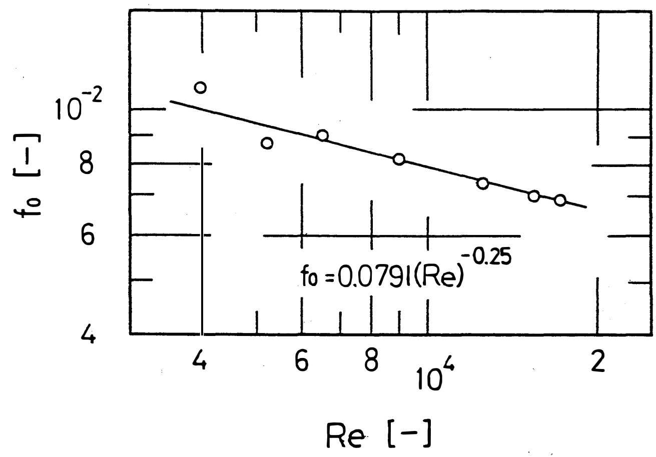


Fig. 6 Friction factor for smooth duct

$$Sh_0 = 0.023\ (Re)^{0.8} (Sc)^{0.4} \quad (5)$$

$$f = 0.0791\ (Re)^{-0.25} \quad (6)$$

$$u^+ = 5.5 + 2.5\,(ln\, y^+)\ \ (y^+ > 30) \quad (7)$$

where, Re is based on equivalent diameter and in range of $4000 < Re < 18000$. These equations agreed with the classical well known ones within experimental errors.

The experimental equation in turbulent convective heat transfer is

$$Nu = 0.023\ (Re)^{0.8} (Pr)^{0.4} \quad (Re > 8000). \quad (8)$$

With the electrochemical method, mass transfer experiments where the concentration on the wall wall is zero are similar to those of heat transfer where the temperature on the wall is constant. Analogy between heat and mass transfer is shown by Eq. (4) and (7).

Next, in order to examine the entrance effects in the interval between the turbulence promoters, the distributions of augmentation ratio Sh/Sh_0 of mass transfer among the turbulence promoters were measured for case of $P/Dp = 11$, $c = 0$ and 3 as shown in Fig. 8. From the data in the figure, it was found that the same distributions were observed downstream from the third promoter. Therefore, the experiment with the promoters was carried out in the section between the third and the fourth promoter, because of safety, though it was reported by the other articles[17, 19] which was repeated in down stream from the second promoter.

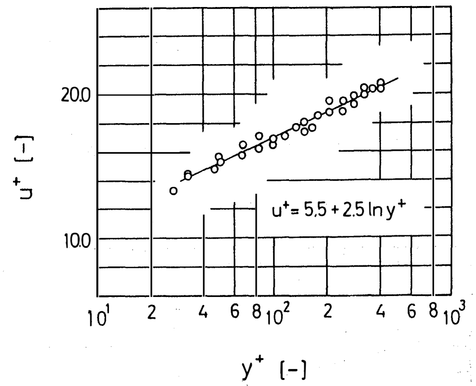


Fig. 7 Velocity profile for smooth duct

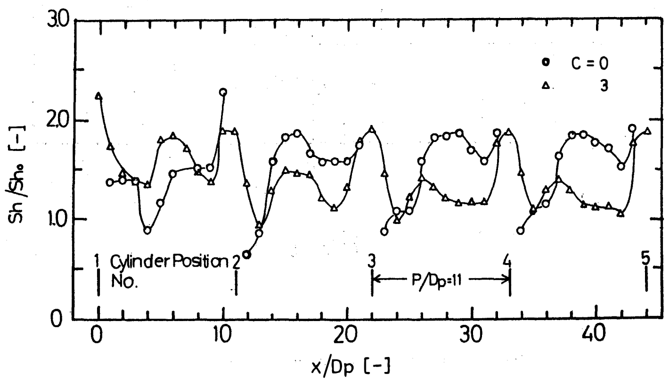


Fig. 8 Check for entrance effect among turbulence promoters

Flow pattern

Flowpatterns among the turbulence promoters in turbulent flow for each P/D_P were clearly classified according the clearance between the promoter and the wall, that is, $c=1$ and $\geqq 3$ as suggested by Miyashita [14] for a single promoter in a rectangular duct. Further, the flow pattern was observed by visualization, in order to examine the effect on P/Dp

(1) In the case of $P/Dp=5$

A typical sketch of the flow pattern. ith clearance for $P/Dp=5$ is shown in Fig. 9.

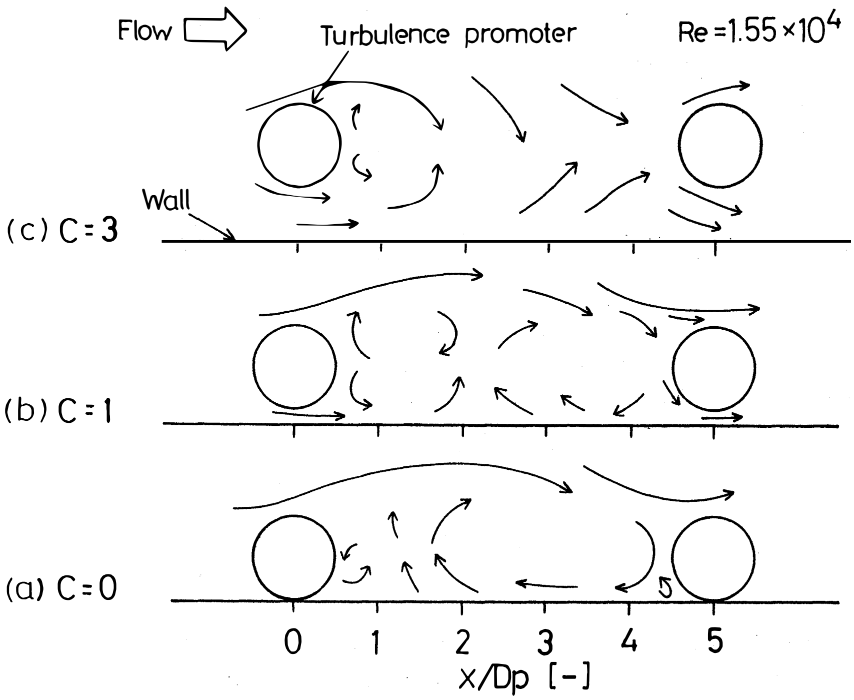


Fig. 9 Flow pattern for $P/Dp=5$ ($Re=1.55 \times 10^4$)

$c=0$:

The flow separated at the top of the promoter was not attached on the wall but collided to the next promoter. It was observed that a part of the flow formed a normal circulating flow among the promoters.

$c=1$:

A couple of normal and reverse circulating flow was observed in the section between the promoter and $x/Dp=2-4$.

$c=3$:

A large scale eddy was formed by the combination of the top and the bottom flow of the promoter and Karman's vortex street was formed in back of the promoter as in the experiment [14] for the single promoter.

In generally, the flow in $p/Dp=5$ seems to stagnate among the promoters because the pitch of promoters is small and the next promoter is located before the wake flow reaches the attachment point.

(2) In the case of $p/Dp=7$

A typical sketch of the flowpattern with clearance for $p/Dp=7$ is shown in Fig. 10.

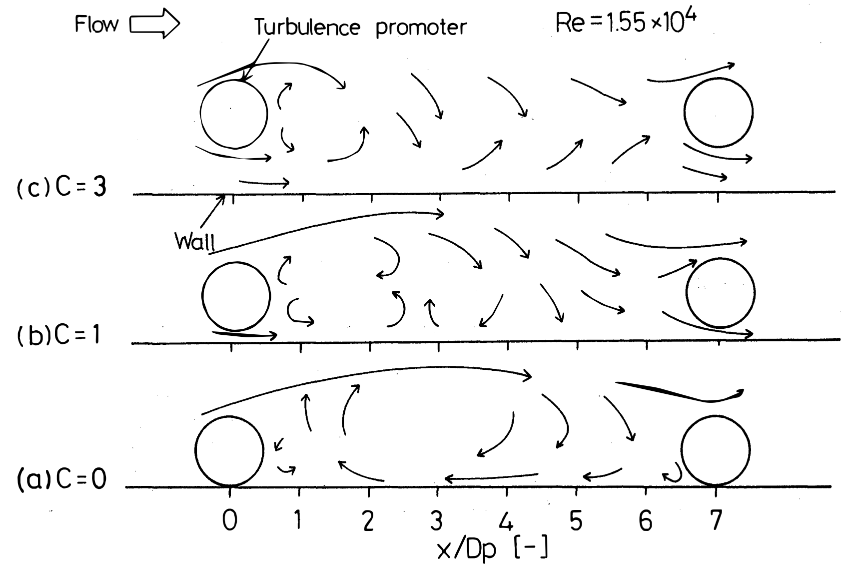


Fig. 10 Flow pattern for $P/Dp=7$ ($Re=1.55 \times 10^4$)

$c=0$:

A part of the seperating flow attaches to the wall near $x/Dp=6$ in front of next promoter. The other flow collides with the next promoter, and normal circulating flow is formed among the promoters.

$c=1$:

The top flowof the promoter attaches near $x/Dp=5$ and the bulk flow behavior appears to make violent turbulence before the next promoter.

$c=3$:

Karman's vortex street is formed in the same way as for $p/Dp=5$, and the effect on the wall due to large scale eddies occuring from the top flow of the promoter was observed in the range of $x/Dp=3$ to 4. It is similar to the flow pattern found in experiments for the single promoter. For $c>3$, Karman's vortex street was formed for all p/Dp.

(3) In the case of $p/Dp=9, 11$ and 16

The flow patterns corresponding to clearance c were recognized as the same as for $p/Dp=7$.

In conclusion, it was found that the flow pattern among the promoters distinguished $p/Dp=5$ from $p/Dp \geqq 7$, flom the behaviors of the separating flow having a direct influence on the augmentation of mass transfer on the wall.

DISTRIBUTION OF LOCAL MASS TRANSFER COEFFICIENT, WALL SHEAR STRESS AND MASS TRANSFER INTENSITY

It may be concidered from the flow pattern that the attachment flow and large scale eddies play important roles for the augmentation of mass transfer among the promoters on the wall. In order to discuss the mechanism of this augmentation, local mass transfer coefficients, wall shear stress and mass transfer intensity among the promoters were measured at clearances $c=0$, 1 and 3, for $p/Dp=5$ and 9 ($p/Dp\geqq 7$), as typical examples of flow patterns. The coefficients were expressed as augmentation ratios, Sh/Sh_0 and $|\tau/\tau_0|$, and then correlated with x/Dp.

(1) General tendency

The augmentation ratio of mass transfer Sh/Sh_0 usually has a peak just under the promoter. This peak occurs at the same location as a peak in the absolute value of the shear stress $|\tau/\tau_0|$ and the place of the minimum value of the mass transfer intensity. Therefore, it appears that the augmentation of mass transfer.was caused by the thin laminar layer of the accelerated flow under the promoter on the wall. Wall shear streys is an important factor against augmentation of mass transfer only at $x/Dp=0$. Because $|\tau/\tau_0|$ is less than unity in all sections except under the promoter.

(2) In the case of $p/Dp=5$

The profiles of Sh/Sh_0, $|\tau/\tau_0|$ and I among the promoters are shown in Fig. 11-(a). (b). (c), for $c=0, 1$ and 3 respectively. For $c=0$, the shape of Sh/Sh_0 and I are only increasing to the

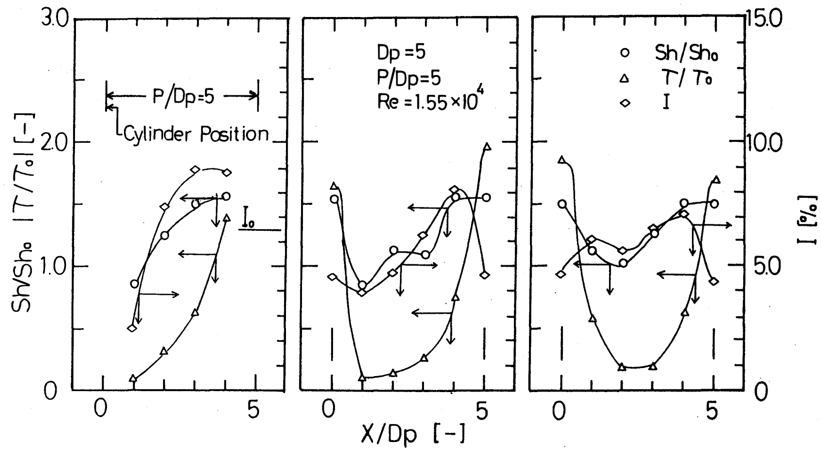


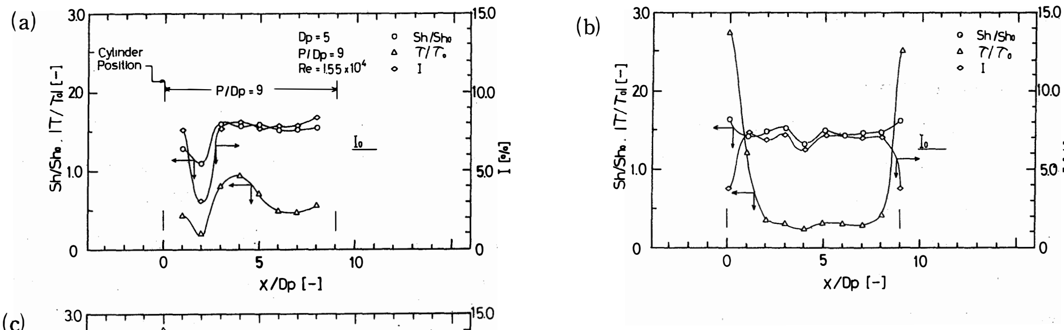
Fig. 11 Profiles of transport factors for P/Dp=5

direction of flow and are similar. Therefore, it may be considered that the augmentation of mass transfer is caused by the turbulence due to the circulating eddy formed among the promoters near the wall. For $c=1$ and 3, both profiles Sh/Sh_0 have minimum values at $x/Dp=1-2$

Then increasing and approaches the values of Sh/Sh_0 at $x/Dp=0$, These profiles are similar to those of the mass transfer intensity I. Therefore, it was concluded that the augmentation at the wall surface is affected significantly by the turbulence which caused by the separating flow or Karman's vortex street formed from the first promoter colliding with the next promoter, was caused by a high value in Sh/Sh_0 at $x/Dp=4$.

(3) In the case of $p/Dp=9$

The profiles of Sh/Sh_0 and among the promoters are shown in Fig. 13-(a), (b), (c) with $c=0, 1$ and 3 respectively. For $c=0$, Sh/Sh_0 have a minimum point at $x/Dp=2$ corresponding to at the stagnation point where reversed flow arises. It is some high values in the wide region of



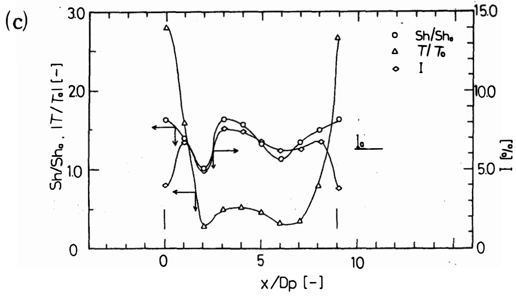


Fig. 12 (a) Profiles of transport factors for P/Dp=9 (c=0)
(b) Profiles of transport factors for P/Dp=9 (c=1)
(c) Profiles of transport factors for P/Dp=9 (c=3)

$x/Dp=3-8$ and is quite similar to the mass transfer intensity profile. Accorbingly, it is recongnized that turbulence due to attachment near the wall is a factor in the augmentation of mass transfer.

For $c=1$, Sh/Sh_0 gives a slightly lower value at $x/Dp=4$ but has high values over the whole range except for just under the promoter. This profile is quite similar to the mass transfer intensity. Accordingly, it is recognized that turbulence due to the attachment flow is also a factor for the augmentation of mass transfer.

For $c=3$, Sh/Sh_0 has a peak at $x/Dp=3-4$ as in the experiments for a single promoter. The peak corresponds to that of the mass transfer intensity. This means that the augmentation of mass transfer is caused by turbulence from Karman's vortex street in the flow pattern.

CONCLUSIONS

An experimental investigation was performed to study the mechanism for the augmentation of heat transfer due to the cylinder type turbulence promoters on the wall in a rectangular duct. In this paper, an electrochemical method using the redox system of ferri/ferrocyanide ion was used in order to measure the mass transfer coefficient, wall shear stress, fluid velocity and mass transfer intensity. The augmentation mechanism of mass transfer among the promoters was explained through the behaviours of the wall shear stress, the mass transfer intensity and the flow pattern by visualization.

Results were as follows.

It was confirmed that the measurement by electrochemical method was correct from the agreement with well known correlations.

The flow patterns were classified by $p/Dp=5$ and $p/Dp\geqq 7$, because of the existance of an attachment point among the promoters, and also classified by the clearance, in $c=0, 1$ and 3. As c increases, a slipping flow occurs just under the promoter and Karman's vortex street is formed downstream of the promoter for $c\geqq 3$ and any p/Dp.

It was found that the attachment flowand large scale eddies play an important role in the augmentation of mass transfer among the promoters through the comparison of profiles of $|\tau/\tau_0|$, I and flowpattern.

$p/Dp=5$: For $c=0$, the augmentation of Sh/Sh_0 depends on the turbulence intensity I. For $c>0$, it depends not only on the increasing $|\tau/\tau_0|$ under the promoter ($x/Dp=0$), but on the turbulence due to large scale eddies among the promoters.

$p/Dp\geqq 7$: For $c=0$, it depends on the turbulence due to the attachment flow among the promoters. For $c>0$, it depends not only on the $|\tau/\tau_0|$ under the promoter but also on the turbulence due to attachment flow, circulating eddies and Karman's vortex ($c\geqq 3$) among the promoters.

NOTATION

A	=surface area of electrode	[cm^2]
c	=clearance between turbulence promoter and wall	[mm]
c_b	=bulk concentration of ferricyanide ion	[mol/cm^3]
D	=diffusivity of ferricyanide ion	[cm^2/s]
Dp	=diameter of turbulence promoter	[mm]
d	=diameter of point electrode	[mm]
F	=Faraday's constant (=$9.652x10^4$)	[c/g-equiv.]
f	=friction factor	[−]
H	=height of rectangular duct	[mm]
I	=mass transfer intensity	[%]
i	=electric current	[A]
k	=mass transfer coefficient	[cm/s]
n_e	=valence charge of an ion	[−]
p	=pitch of turbulence promoter	[mm]
Re	=Reynolds number	[−]
Sc	=Schmidt number	[−]
Sh	=Sherwood number	[−]
u^+	=non-dimensional velocity ($U/(\sqrt{\tau/\rho})$)	[−]
U	=mean velocity	[cm/s]
u	=free stream velocity	[cm/s]
y^+	=non-dimensional distance from wall	[−]
x, y	=coordinates of test section	[mm]
μ	=viscosity	[pa. s]

ρ =density [g/cm^3]
τ =shear stress [g/cm. s^2]

subscripts

o =smoothed duct

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This anticle was originally presented in International Journal of chemical Engineering" chemical Engineering Communication"

(Received October 31, 1984)