HEAT TRANSFER CORRELATION IN HIGH PRANDTL (HIGH SCHMIDT) NUMBER FLUID IN VOTATOR TYPE SCRAPED SURFACE HEAT EXCHANGER

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An experimental investigation to obtain heat transfer correlation in a Votator type scraped surface heat exchanger with two-blades was performed by an electro-chemical method. Measurements were carried by mass transfer under diffusion control in a ferricyanide/ferrocyanide redox electrochemical reaction. The heat transfer correlation was obtained from an analogy of heat and mass transfer. Local heat transfer coefficients on the wall of the outer column of the exchanger was measured by varying the rotational Reynolds number, flow rate of fluid, Prandtl number and equivalent diameter in order to obtain the unity thermal design equation.

The time averaged local Nusselt number in a high Prandtl number fluid was found to be correlated by the following equation:

$$Nu = 1.53 Re_r^{0.51} Pr^{0.33} (D_o/D_e)^{0.44} \\ (1320 < Pr < 5810, 2.94 < D_o/D_e < 7.2)$$

where Re_r and D_e are the blade rotational Reynolds number and equivalent diameter respectively.

Introduction

It is well known that mechanical agitation within the bulk of a process liquid or near a vessel wall enhances the heat transfer between the wall and the bulk liquid. Fluid processing using a rotating scraping blade against the surface of an outer column is called either "close clearance equipment" or a "mechanically-aided thermal processor". It is effectively used for active heat transfer enhancement or chemical reactions in the chemical industries. The liquid can either fill the entire column or flow as a thin film along the column wall surface. In purely heat transfer application, such a device is commonly called a scraped surface heat exchanger; when the liquid is filled in the vessel and then flows in an annulus between the outer surface and the rotor shaft with blades, it is referred to as a votator type scraped surface heat exchanger. These devices have a short residence time, high heat transfer coefficient and a low hold-up, and hence are effective in processing of viscous liquids.

Many investigators have comprehensively studied the scraped film heat exchanger in which the

liquid is subjected to gravitational and centrifugal forces as the blades rotate and scrape it from the outer heat transfer surface. For instance, Kern *et al.* (1959), Kool (1958), Harriott (1959), Azoory *et al.* (1970) and Miyashita (1978) investigated the characteristics of heat transfer, Skelland *et al.* (1962), Trommelen *et al.* (1971) and Toh *et al.* (1981) the agitation power used against rotational blades, and Kern (1959) and Nakamura (1978) the flow behavior in the exchanger. For the votator type scraped surface heat exchanger in which the liquid fills the annulus section, Niida *et al.* (1978) investigated flow behavior in the cross section of the annulus, and Houlton (1944), Skelland (1962), and Trommelen (1971) the characteristics of heat transfer.

However, more useful correlations of thermal design equation have not been proposed recently. Since the fluid mechanical and heat transfer phenomena occurring in such a system are very complex, analysis of heat transfer mechanisms must be based on a simplified model.

The object of this study is to measure indirectly the instantaneous heat transfer coefficient at each point in the exchanger and to obtain its correlation on operation factors, apparatus factors and physical properties.

In this study, an electrochemical method

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Solution	Composition [kmol/m ³]			T [K]	ρ [kg/m ³]	C_p [J/(kg·K)]	$\mu \times 10^3$ [Pa·s]	$D \times 10^{10}$ [m ² /s]	Sc
	NaOH	K ₄ Fe(CN) ₆	K ₃ Fe(CN) ₆						
A	1	0.005	0.005	303	1023.6	4060	0.993	7.349	1320
B	1	0.005	0.005	297	1039.4	4060	1.110	6.502	1642
C	2	0.005	0.005	303	1076.1	3947	1.243	5.766	2003
D	2	0.005	0.005	297	1078.2	3947	1.386	5.120	2511
E	4	0.005	0.005	303	1145.7	3767	1.943	3.657	4637
F	4	0.005	0.005	297	1150.7	3767	2.181	3.262	5810

(Mizushina, 1971) was used to develop such a study. The heat transfer coefficients for high Prandtl number fluid were obtained from translation of mass transfer coefficients based on an analogy between heat and mass transfer.

The schematic diagram of the experimental apparatus is shown in **Fig. 1**. The electrolyte was pumped by a magnet pump (3) from a storage tank (1) controlled thermally. The electrolyte flowed through a flow valve (4), an orifice meter (5), and a heat exchanger (6) and then back to the reservoir through the scraped surface exchanger (8).

stainless steel

process fluid in-let

anode (+)

100

100

100

100

200

144

shaft diameter (110)

process fluid out-let

transfer wall

isolated cathode (-)

0.15

1.0

12.0

isolated platinum cathode (-)

plastic insulation

recorder (visi-graph)

battery (+, -)

resin tubing in order to minimize corrosion effects.

Figure 2 indicates the details of the scraped surface heat exchanger and the circuitry for measuring the current (and hence the mass transfer coefficient). The exchanger consists of stainless steel 0.144 m in inside diameter and 0.6 m long. Three kinds of rotor shaft (0.095, 0.110 and 0.124 m in shaft diameter) housed two blades made of resin.

The clearance of the annulus section was changed by three variables. Four isolated nickel electrodes (cathodes) on the tube wall, the details of which are shown in Fig. 2, were located at 0.1 m intervals from the top along the axis. The other parts of the tube were used as the anode.

The instantaneous current through a given electrode was determined by measuring the instantaneous voltage across a known resistance. This voltage was recorded by a Visigraph (recording oscillograph) which employs mirror galvanometers with high frequency response.

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2. Calculation of Heat Transfer Coefficients

The mass transfer coefficients were measured by using the ferricyanide/ferrocyanide redox electrochemical reaction in which

The details of the method have been reviewed by Mizushima (1971). The basis of the method is that the electrochemical phenomena under the so called 'limiting current' condition are limited only by mass transfer at the cathode electrode and hence the concentration of the ferricyanide ion is zero at the electrode. Mass transfer limitation does not occur at the anode, because its transfer area is very large relative to that of the cathode.

Under these conditions, the mass transfer coefficient is given by

$$k_m = \frac{i}{n_e F A C_b} \quad (1)$$

To obtain heat transfer coefficients, it is assumed that an analogy exists between heat and mass transfer. The heat transfer system is similar to that at constant wall temperature.

3. Experimental Results

Since the instantaneous current is a direct measurement of the instantaneous mass transfer coefficient, it is possible to obtain a time-averaged mass transfer coefficient by integrating these point values to give the time-averaged current to be used in Eq. (1).

Figure 3 shows the variation in the integrated average current with axial position as measured by the four different electrodes operating separately. Only at the upper electrode does the current decrease slightly, since this decrease is greater at lower rotational speeds, it can be attributed to entrance effects by means of liquid distribution. The results reported here are for the third electrode from the top of the column ($H=0.3$ m).

Figure 4 shows the relationship between the mass transfer coefficients and the rotational speed for different Schmidt numbers and a constant mass flow rate.

To check the mass flow rate effect, the average mass transfer coefficient is plotted in Fig. 5 against the mass flow rate for various rotational speeds at constant $D_o/D_e=2.94$, where D_e is the equivalent diameter of the annulus section ($D_e=D_o-D_i$). It can

Fig. 3 Variation in average current (axial)

Fig. 4 Relation of mass transfer coefficients and rotational speed ($D_o/D_e=2.94$)

Fig. 5 Effect of mass flow rate with rotational speed ($Sc=1320$, $D_o/D_e=2.94$)

be seen that the mass transfer coefficient is almost independent of mass flow rate, though the effects appear only slightly at lower rotational speeds.

Since essentially, bulk fluid flows in the exchanger, it is expected that the coefficient depends on the mass flow rate. Figure 5 means that there is

Fig. 6 Effect of D_o/D_e against Sh

Fig. 7 Effect of Sc against Sh

stronger dependence on rotational speeds than the mass flow rate.

On the other hand, Miyashita *et al.* (1978) pointed out that the dependence of the heat transfer coefficients on mass flow rate can be expressed as a power law with rotational speed in a scraped film heat exchanger having two blades.

Figure 6 shows the Sherwood number against D_o/D_e with two kinds of rotational Reynolds number ($Re_r=2000$ and 4000) at constant mass flow rate ($W=0.628$ kg/s). It can be seen from this figure that Sh is proportional to $(D_o/D_e)^{0.44}$.

In order to check the influence of the Sc number, the experiment was carried out using six kinds of Schmidt number shown in Table 1. Figure 7 shows Sh vs. Sc with three kinds of rotational Reynolds numbers at constant D_o/D_e . As a result, Sh is proportional to $Sc^{0.33}$.

To summarize the results obtained, they are presented as shown in Fig. 8 which provides the desired correlation. Though the data show very little scatter about the optimum straight line, the following equation on the mass transfer coefficient is obtained

Fig. 8 Plots of data according to correlating Eq. (2)

for a Votator type scraped surface heat exchanger.

$$Sh = 1.53 Re_r^{0.51} Sc^{0.33} (D_o/D_e)^{0.44} \quad (2)$$

The exponent on the rotational Reynolds number determined from the straight line is 0.51.

4. Discussion and Conclusion

Assuming the analogy for heat and mass transfer in high Prandtl (high Schmidt) number fluid, the Eq. (2) can be replaced by the following Eq. (3).

$$Nu = 1.53 Re_r^{0.51} Pr^{0.33} (D_o/D_e)^{0.44} \quad (3)$$

($1320 < Pr < 5810$, $2.94 < D_o/D_e < 7.2$)

Considering that the rate of heat transfer depends more strongly on the rate of transfer conduction in frequent renewed layers than on the rate of steady state convection, the heat transfer phenomena occurring on such a exchanger surface is quite similar to the penetration surface renewal models of Higbie (1938). The heat transfer coefficient is therefore calculated from the following equation.

$$h(T_w - T_b) = -k \left(\frac{dT}{dx} \right) \Big|_{x=0} \quad (4)$$

where the derivative is obtained from the solution of the transient conduction equation:

$$\frac{\partial T}{\partial \theta} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (5)$$

as applied to the process liquid. Integrating Eq. (4) over the contact time θ yields the time-averaged local heat transfer coefficient as:

$$h = \frac{2}{\sqrt{\pi}} \left(\frac{C_p \rho k}{\theta} \right)^{1/2} \quad (6)$$

Fig. 9 Comparison with present result and other correlations

where $\theta = 1/(nN)$, which upon simplifying and in dimensionless terms, becomes

$$Nu = \frac{2}{\sqrt{\pi}} (Re_r Pr)^{0.5} \quad (7)$$

Equation (7) cannot be compared directly with the empirical Eq. (3) because of the dependence on a power of Pr and D_o/D_e . In order to compare with the model, Nu versus Re_r was plotted at constant Prandtl number ($Pr=1320$) as shown in Fig. 9. Here, D_o and D_i applied the size to be used in the present experiment.

In the figure, the present result is lower than the penetration model, and higher than Trommelens's Correlation for high Prandtl number fluids. It should be noted that three correlations are different from the dependence of the Prandtl number. However, our correlation for high Prandtl number fluids almost agrees with other ones.

As results: (1) an electrochemical method has been used successfully for the investigation of the heat transfer phenomena in scraped surface type heat exchangers; (2) and the time-averaged heat transfer coefficient for high Prandtl fluid ($1320 < Pr < 5810$) in the Votator type scraped surface heat exchanger with two blades is correlated by Eq. (3).

Nomenclature

A	= electrode area	[m ²]
C_b	= bulk concentration of solution	[mol/l]
C_p	= heat capacity	[W/K]

D_e	= equivalent diameter ($=D_o-D_i$)	[m]
D_i	= diameter of rotor shaft	[m]
D_o	= inner diameter of column	[m]
D_m	= diffusivity	[m ² /s]
F	= Faraday's constant	[C/mol]
h	= heat transfer coefficient	[W/(m ² ·K)]
i	= electric current	[A]
k	= thermal conductivity	[W/(m·K)]
k_m	= mass transfer coefficient	[m/s]
n	= number of blades on rotor shaft	[—]
N	= rotational speed	[1/s]
Nu	= Nusselt number ($=hD_e/k$)	[—]
Pr	= Prandtl number ($=C_p\mu/k$)	[—]
Re_r	= rotational Reynolds number ($=D_e^2nN\rho/\mu$)	[—]
Sc	= Schmidt number ($=\mu/\rho D_m$)	[—]
Sh	= Sherwood number ($=k_mD_e/D_m$)	[—]
T	= temperature	[K]
V	= velocity of fluid	[m/s]
W	= mass flow rate	[kg/s]
ρ	= density of fluid	[kg/m ³]
μ	= viscosity of fluid	[Pa·s]
θ	= contact time	[s]

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