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PRESSURE DROP AND MASS TRANSFER IN DILUTE POLYMER SOLUTIONS IN TURBULENT DRAG-REDUCING PIPE FLOW

R. SMITH and M. F. EDWARDS

Schools of Chemical Engineering, University of Bradford, Bradford BD7 1DP, U.K.

and

H. Z. WANG

Institute of Chemical Engineering, Peking, People's Republic of China

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Abstract—An extensive experimental investigation has been carried out into pressure drop and mass transfer in aqueous solutions of Polyox (polyethylene oxide) in turbulent pipe flow. The method of diffusion controlled electrolysis was used for the mass transfer measurements. It was found that pumping the Polyox solutions with a centrifugal pump caused rapid shear degradation which considerably reduced the drag-reducing properties of the solutions, decreased viscosities and increased diffusion coefficients. The experimental mass transfer data for both the fresh and the degraded solutions were compared with predictions using eddy viscosity correlations. Excellent agreement was obtained. The method of prediction does not depend on measured heat or mass transfer data but on friction data only.

NOMENCLATURE

b,	constant in equation (2);
A, B,	constants in the logarithmic law of the wall;
C_b,	bulk molar concentration [kmol m^{-3}];
C_f,	Fanning friction factor, $2\tau_w/(\rho\langle v_z\rangle^2)$;
C_m,	the Stanton number, $k_L/\langle v_z\rangle$, dimensionless mass transfer coefficient;
D,	pipe diameter [m];
$\mathscr{D}$,	molecular diffusivity [m^2 s^{-1}];
F,	Faraday's constant [C kg^{-1} equiv.];
I,	current density [A m^{-2}];
k_L,	mass transfer coefficient [m s^{-1}];
L,	electrode length [m];
r,	radial distance [m];
R^+,	dimensionless pipe radius, $\rho R v^*/\mu$;
Re,	Reynolds number, $\rho\langle v_z\rangle D/\mu$;
Sc,	Schmidt number, $\mu/\rho\mathscr{D}$;
Sc_{tr},	turbulent Schmidt number, $\varepsilon_{rz}/\varepsilon_{mr}$;
Sh,	Sherwood number, $k_L D/\mathscr{D}$;
T,	temperature [K];
v_z^+,	dimensionless velocity, v_z/v^*;
$\langle v_z\rangle$,	mean velocity [m s^{-1}];
v^*,	friction velocity, $(\tau_w/\rho)^{1/2}$ [m s^{-1}];
y^+,	dimensionless distance from pipe wall, $\rho y v^*/\mu$;
z,	axial distance [m];
Z,	ionic charge.

Greek symbols

ε_{mr},	eddy diffusivity for mass in the radial direction [m^2 s^{-1}];
ε_{rz},	eddy viscosity [m^2 s^{-1}];
μ,	viscosity [kg m^{-1} s^{-1}];
ρ,	density [kg m^{-3}];
τ_w,	wall shear stress [N m^{-2}].

Subscripts

N,	Newtonian value;
0,	at the pipe centre;
w,	at the pipe wall;
1,	at the boundary between the wall and logarithmic regions of the flow;
2,	at the boundary between the logarithmic and turbulent core regions of the flow.

INTRODUCTION

THE ADDITION of very small concentrations of high polymeric materials can reduce the frictional resistance in turbulent flow to as low as one-quarter that of the pure solvent. This phenomenon, drag reduction, can occur with fluids which exhibit both Newtonian and non-Newtonian viscosity characteristics. Drag reducing behaviour may be an inherent property of the fluid or may have resulted from the use of additives with a solvent to achieve particular rheological characteristics.

The present work is concerned with frictional resistance and fully developed mass transfer for the flow of dilute polymer solutions in turbulent pipe flow. McConaghy and Hanratty [1] used diffusion controlled electrolysis to study both entry region and fully-developed mass transfer for the flow of dilute polymer solutions in turbulent pipe flow. They found that an analogy between momentum and mass transfer gave poor predictions of their mass transfer data. In the present study an extensive experimental investigation into pressure drop and fully-developed mass transfer in aqueous solutions of Polyox (polyethylene oxide) has been carried out using the diffusion controlled electrolysis experimental method. Diffusion coefficients were also measured in order that the turbulent mass transfer data could be interpreted. The experimental data have been compared with a method of prediction described previously [2]. This method has been used previously with success to predict heat transfer to non-Newtonian and drag-reducing fluids in turbulent pipe flow [2]. In contrast with predictive methods described by other workers (see for example ref. [3]) the method used in the present paper attempts to predict mass transfer rates directly from friction factor data without any reference to measured heat or mass transfer data.

EXPERIMENTAL TECHNIQUE

In the work reported in this paper the method of diffusion controlled electrolysis [4] was used to measure the rate of diffusion of an ionic species through aqueous polymer solutions to an electrode surface.

The electrochemical reaction used in the experimental programme was the reduction of ferricyanide ion at a nickel cathode,

$$\mathrm{Fe(CN)_6^{3-}} + e \rightarrow \mathrm{Fe(CN)_6^{4-}}.$$

A solution containing approximately equimolar quantities of ferri- and ferrocyanide ions at concentrations of 5×10^{-3} M was used. The concentration of ferricyanide was measured experimentally using standard iodometric titration procedures and checked several times during the course of a test. Sodium hydroxide was used as the supporting electrolyte at a concentration of either 0.5 or 1.0 M. Care was taken with the ferri–ferrocyanide solutions to exclude oxygen which can cause errors in the electrochemical measurements.

Polymeric solutions were made by dissolving Polyox (polyethylene oxide) in distilled water then adding the sodium hydroxide and degassing with nitrogen before adding the ferri–ferrocyanide. Polyox was used in the concentration range 500–3000 ppm.

The viscosity of the solutions was measured in an Ubbelohde viscometer. Several samples were taken during the course of a test to check for degradation. Small reductions in viscosity were experienced in some of the tests after the polymer solutions had been pumped using a centrifugal pump. These changes in properties of the polymer solutions due to pumping are discussed more extensively in subsequent sections.

EXPERIMENTAL APPARATUS

A flow loop was constructed in which both laminar and turbulent flow studies could be carried out. The general arrangement is shown in Fig. 1. The 0.15 m^3 storage and mixing tank was constructed from Ni–Cr–Mo stainless steel. The test solutions were made and mixed in the tank by means of a 6-bladed turbine impeller using a low speed. A cooling coil was used to regulate the fluid temperature and a nitrogen sparge was fitted to the base of the tank. In addition, a nitrogen connection on the tank cover allowed the vessel to be pressurised, thus supplying a constant liquid flowrate to the test section driven by gas pressure. Liquid could also be circulated from the tank

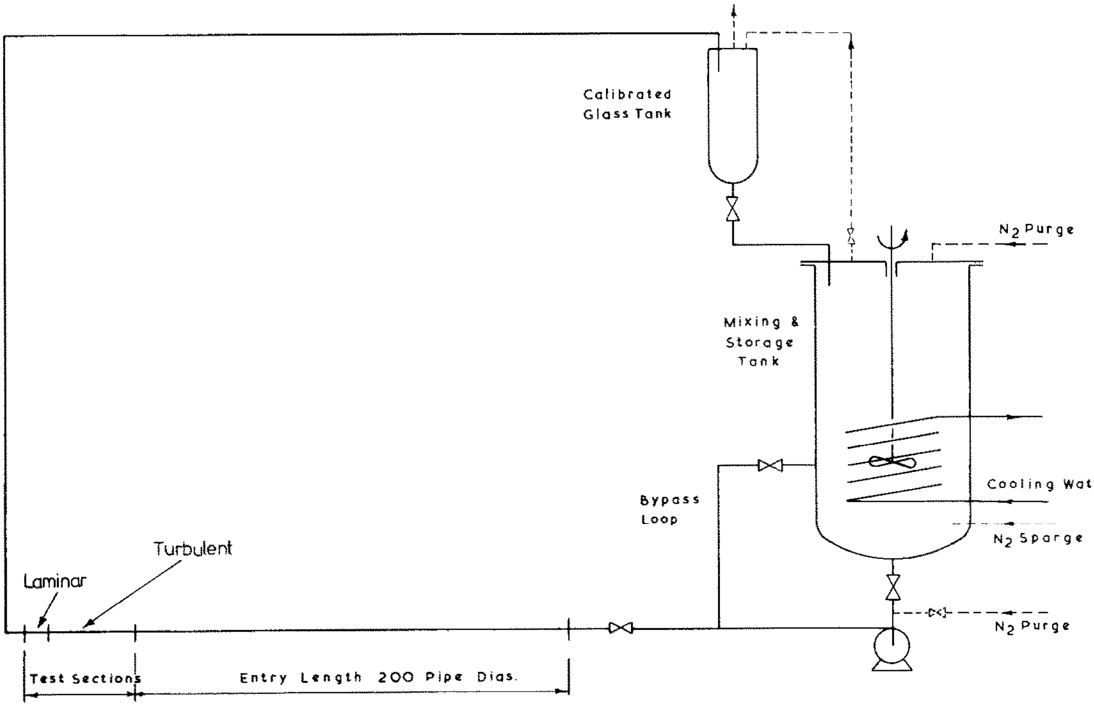


FIG. 1. General arrangement of flow loop used for pipe-flow studies.

by means of a PVC centrifugal pump. All the pipework and valves were constructed from PVC or Perspex and a long, straight entry section of 200 pipe diameters was fitted before the test section to permit complete development of the velocity profile. To measure the flowrate of liquid, a 0.015 m^3 calibrated, glass collecting-tank was used. Other flow measuring devices were not employed because of the presence of polymer in the test liquids.

Diffusivities were measured by applying the theoretical solution of Leveque to a developing concentration boundary layer for laminar flow past a short electrode. The theory, equipment and experimental technique have been reported previously [5]. If this developing concentration boundary layer is thin it can be assumed that within the layer the velocity gradient is constant and equal to the velocity gradient at the wall. Under such conditions with a Newtonian liquid, the current is given by [5]

$$I = 1.62\frac{\mathscr{D}ZFC_b}{D}\left[\frac{\langle v_z\rangle D^2}{\mathscr{D}L}\right]^{1/3}. \qquad (1)$$

This is the mass transfer analogy of the Leveque solution in heat transfer and it is valid if $\langle v_z\rangle D^2/\mathscr{D}L >$ 100 approximately. Thus it is possible to calculate the diffusion coefficient of an ionic species in a Newtonian liquid by measuring the current density at an electrode in steady laminar pipe flow. Furthermore, the diffusion coefficient applies at the wall shear rate which is known. Measurements were taken at several flowrates for each test to indicate the effect, if any, of shear rate on diffusivity.

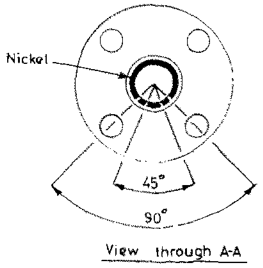
The intention of the turbulent flow studies was to take measurements in a fully developed concentration boundary layer. The test section arrangement adopted for the turbulent flow measurements is shown in Fig. 2. A flow entry section of 20 diameters was used (in addition to the large entry length for the laminar flow studies). The cathode/anode section was constructed from three pieces of nickel such that the area of cathode under study was completely surrounded by guard cathode, 10 diameters of guard being allowed upstream and one downstream. The measurements of Shaw, Reiss and Hanratty [6] indicated that a mass transfer entry length of 10 diameters would be more than ample. The joint between cathode and guard cathode was made with Araldite and was kept as small as practical (0.2 mm). The test sections were constructed by cementing nickel tube sections inside a Perspex tube with Araldite. The bores were then honed to give a precision bore (± 0.005 mm) with a high quality finish. The construction of the laminar test section has been reported previously [5]. To minimise flow disturbances at the flanges, a fluid seal was achieved using neoprene 'O' rings. The sections were aligned by pushing a Teflon plug (which was a push fit) through the bore to the joints before bolting the flanges together.

Anode : cathode area ratios were 5 : 1 for the laminar test section and 9 : 1 for the turbulent arrangement. Test electrodes were cleaned using smooth carborundum paper (wet), degreased and washed with water. The electrodes were then treated cathodically in 1 M NaOH to produce hydrogen evolution for 10–15 min. The electrical circuit used for the measurements has been described previously [5]. All current–voltage curves including those for solutions containing Polyox exhibited distinct plateau regions, indicating diffusion-controlled conditions.

TURBULENT FRICTION FACTOR MEASUREMENTS

Water was used to test the accuracy of the apparatus for friction factor measurements. Data for water were taken up to a Reynolds number of 3.1 × 10^4 and are shown in Fig. 3. These data are seen to be within 5% of the Nikuradse equation.

Figure 3 also shows friction factor data for solutions of Polyox in pure distilled water. It is important to note that flow was induced for these measurements using nitrogen pressure to drive the flow. In some cases, the fluid was then pumped around the flow loop using the centrifugal pump for a few minutes and the measure-



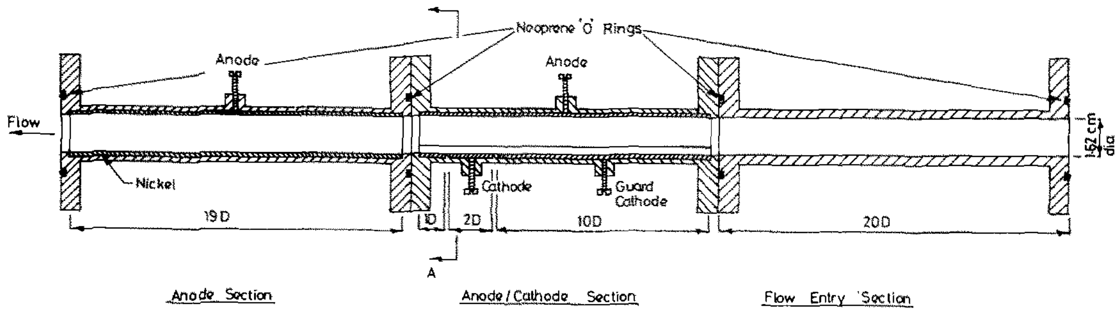


FIG. 2. Test sections used for turbulent studies.

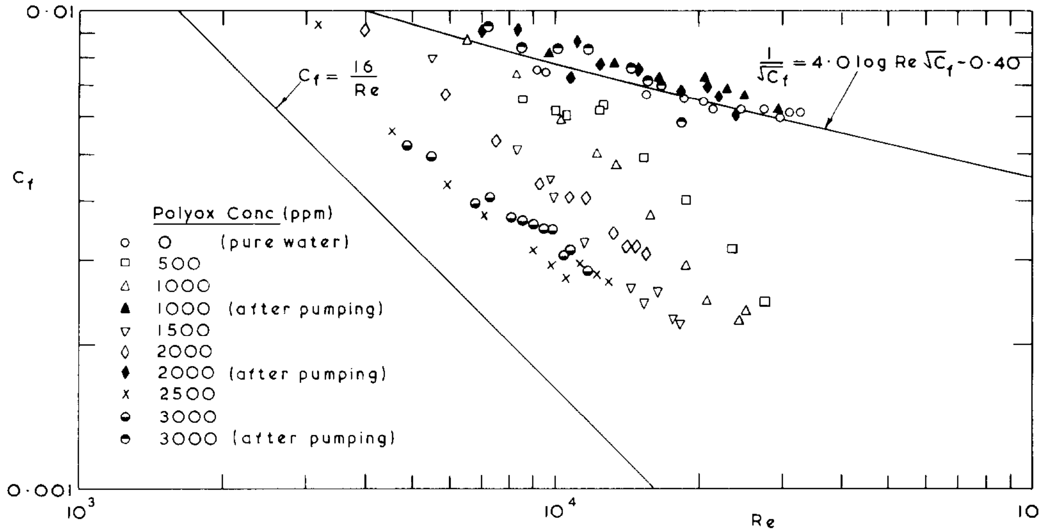


Fig. 3. Friction factor data for Polyox in the absence of electrolyte.

ments repeated. It can be seen from Fig. 3 that the centrifugal pumping action caused shear degradation which considerably reduced the drag-reducing properties of the solutions. Not only did the friction factor data increase but some were in excess of the data for pure water.

This degradation, observed in pumping, is an important limiting factor in the use of Polyox solutions and shows the need to avoid large shear rates if the drag-reducing action is to be maintained.

Further pressure drop measurements were taken at the same time as the mass transfer measurements with sodium hydroxide and potassium ferri–ferrocyanide added to the polymer solutions. These are shown in Fig. 4. The presence of electrolyte was found to have a considerable effect on the drag-reducing properties of the polymer solutions. The drag-reducing effect was greatly reduced and this presents a severe problem for work using the electrochemical technique when an excess of basic reagent is used. It is difficult to obtain strongly drag-reducing Polyox solutions for use with the electrochemical method. Alternative electrolyte systems not employing caustic material have been used by some workers [1, 7]. However, these require electrode materials other than nickel which can introduce difficulties into electrode design and construction.

Clearly, the solutions must be treated carefully as shearing causes a further loss of activity as seen in Fig. 4. Initially, gas pressure was used to drive the flow and subsequently the centrifugal pump was used to study the characteristics of the solutions after shear degradation. Again the degrading effect of the pump is clear, the data after pumping showing much higher friction factors than before pumping, indeed many of the data are above the Nikuradse equation.

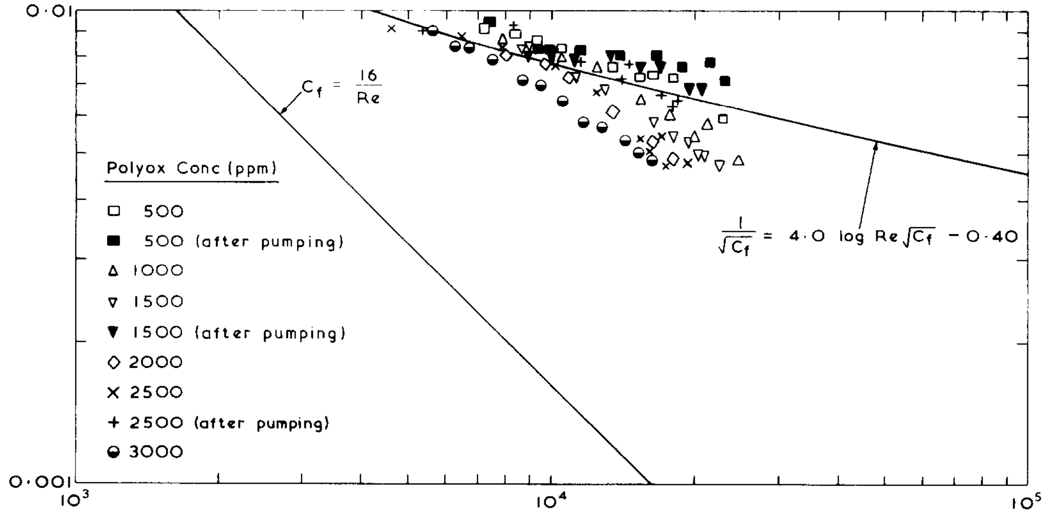


Fig. 4. Friction factor data for Polyox solutions in 0.5 M sodium hydroxide and 0.005 M potassium ferri–ferrocyanide taken during the mass transfer measurements.

Table 1. Diffusivities for 1 M NaOH solutions

Temp (°C)	$\mathscr{D} \times 10^{10}$ ($m^2 s^{-1}$)	$\mathscr{D}\mu/T \times 10^{15}$ ($kg\,m\,s^{-2} K^{-1}$)
20	6.104	2.33
20	6.338	2.42
20	6.094	2.33

Table 2. Diffusivity for Polyox solutions in 0.5 M NaOH

Polyox concentration (ppm)	Before pumping			After pumping		
	Temp. (°C)	$\mathscr{D} \times 10^{10}$ ($m^2 s^{-1}$)	$\mathscr{D}\mu/T \times 10^{15}$ ($kg\,m\,s^{-2} K^{-1}$)	Temp. (°C)	$\mathscr{D} \times 10^{10}$ ($m^2 s^{-1}$)	$\mathscr{D}\mu/T \times 10^{15}$ ($kg\,m\,s^{-2} K^{-1}$)
500	19.5	5.194	2.07	22.5	5.991	2.35
1000	20.0	4.991	2.27	20.5	5.878	2.24
1500	19.2	4.955	2.51	19.1	6.255	3.09
2000	17.8	5.003	3.08	17.8	5.687	2.97
2500	19.5	5.229	3.02	21.0	5.847	3.33
3000	20.0	5.101	3.65	20.0	5.804	3.82

DIFFUSIVITY MEASUREMENTS

Initial measurements were carried out with solutions of potassium ferri–ferrocyanide in sodium hydroxide without any polymeric additive. These results are presented in Table 1. The agreement between these data and previously published data [5] is very good.

Further tests were carried out on solutions containing various concentrations of Polyox (Table 2). The actual diffusion measurements were taken under laminar flow conditions in all cases by pressurising the storage tank, shown in Fig. 1, with nitrogen. Subsequent tests showed that pumping the Polyox solutions with the centrifugal pump for even 2 or 3 min in the flow loop caused an irreversible change in the nature of the solutions. This change was indicated by decreases in viscosity of up to 15%, increased diffusivity (Table 2) and by the pressure drop and mass transfer behaviour in turbulent flow. These data also show that the commonly used assumption of constant $\mathscr{D}\mu/T$ is not valid for systems containing polymeric additives. This is in agreement with previous findings [5]. Clearly, extrapolation of diffusivity data using the assumption of constant $\mathscr{D}\mu/T$ for polymer solutions could lead to serious errors.

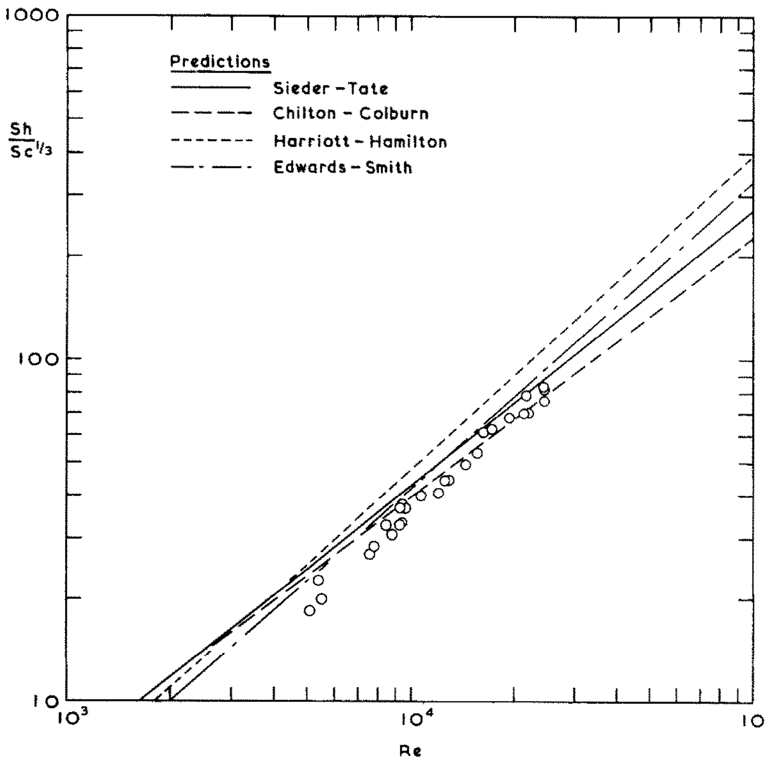


FIG. 5. Mass transfer data for sodium hydroxide solutions.

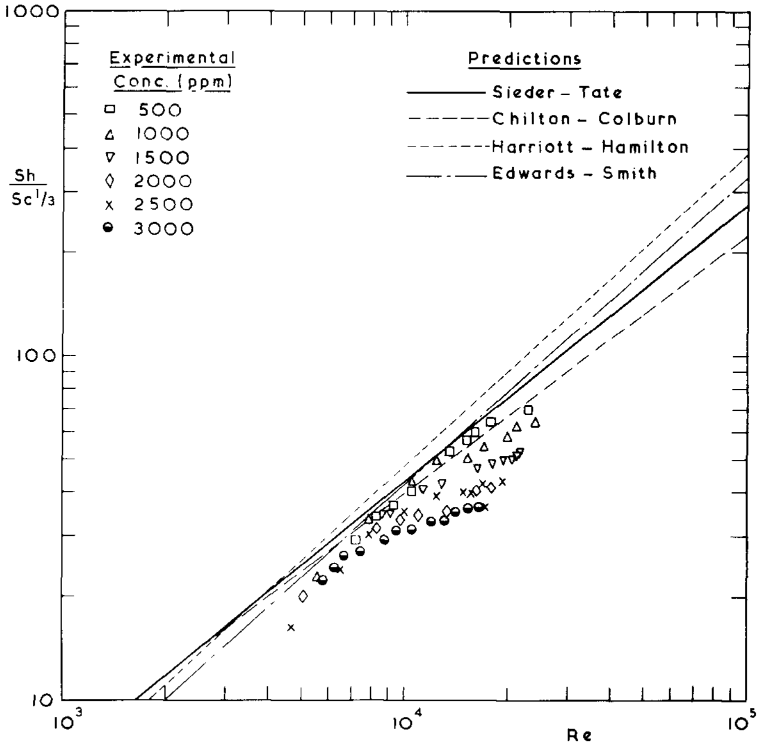


FIG. 6. Mass transfer data for Polyox solutions before subjecting fluids to pumping with a centrifugal pump.

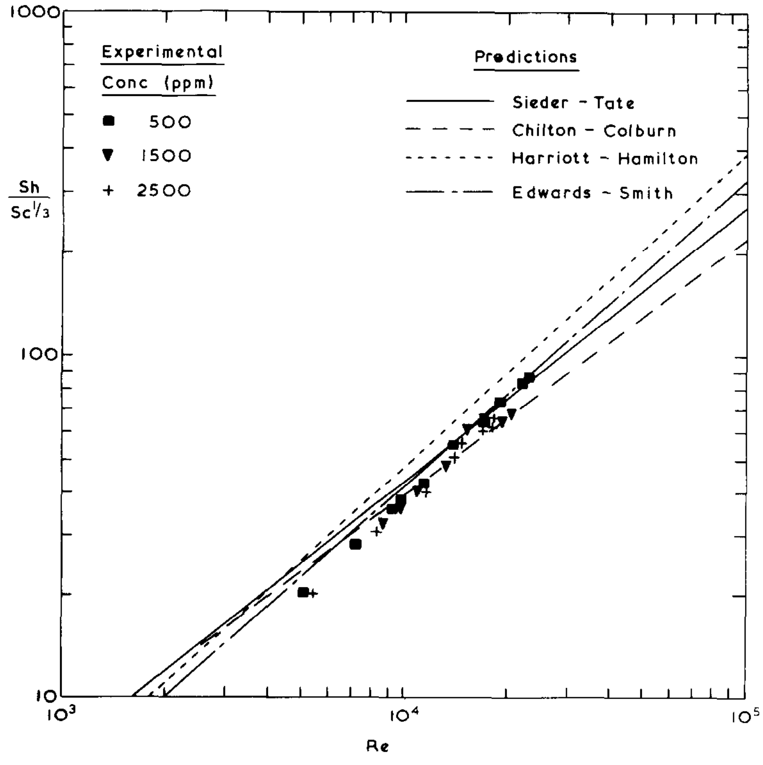


FIG. 7. Mass transfer data for Polyox solutions after subjecting fluids to pumping with a centrifugal pump.

No significant effect of shear rate upon diffusion coefficient was observed at any of the polymer concentrations studied. Previous results with polymers other than Polyox sometimes showed a significant effect of shear rate upon diffusivity [5]. The diffusion results from the present work are summarised in Table 2.

TURBULENT MASS TRANSFER MEASUREMENTS

To test the accuracy of the experimental techniques for turbulent mass transfer a series of measurements were carried out on solutions containing only sodium hydroxide and potassium ferri–ferrocyanide. These data are presented in Fig. 5 and compared with the correlations of Chilton–Colburn [8], Seider–Tate [9], Harriott–Hamilton [10] and Edwards–Smith [11]. The latter expression is given by

$$Sh = 0.1646\, b^{1/3}\, Re^{0.875}\, Sc^{1/3} \qquad (2)$$

where b is a parameter in the eddy viscosity expression of Mizushina and Ogino [12]. Equation (2) is in fact capable of accounting for drag-reducing effects via the parameter b. However, in Fig. 5 the value of the parameter b appropriate to Newtonian liquids was used.

Turbulent mass transfer data were than taken for Polyox solutions using nitrogen pressure flow and afterwards using the centrifugal pump. Figure 6 shows data taken using flow driven by nitrogen pressure before any pumping at all with the centrifugal pump. Figure 7 shows data taken using the centrifugal pump.

A comparison of the data in Figs. 6 and 7 again shows that pumping causes a change in the nature of the solutions. Figure 6 indicates mass transfer rates for polymer solutions which are much lower than those for pure solutions shown in Fig. 5. The relationship between friction factor and mass transfer behaviour is clearly seen by comparing Figs. 4 and 6. Those solutions which show the lowest friction factors also show the lowest mass transfer rates.

A curious feature of some of the friction factor data taken for polymer solutions after pumping shown in Fig. 4 is that these data tend to lie above the Nikuradse correlation. It can be seen from Figs. 4 and 7 that these same conditions produce mass transfer rates marginally in excess of those in the pure solutions. This is a most interesting phenomenon which has not been reported previously.

COMPARISON BETWEEN EXPERIMENTAL DATA AND PREDICTIONS FROM EDDY VISCOSITY CORRELATIONS

In Figs. 6 and 7 the experimental data for polymer solutions have been compared with predictions of mass transfer for Newtonian liquids. However, a theoretical approach to the calculation of heat transfer coefficients for non-Newtonian and drag-reducing fluids in pipe flow has been reported previously and applied to heat transfer data [2]. It was demonstrated in this work that four Newtonian eddy viscosity correlations could be successfully adapted to predict heat transfer coefficients. The theory which was outlined for heat transfer can be applied to the mass transfer measurements of the present study using the analogy between heat and mass transfer. In this approach [2], experimentally obtained friction factor data can be used to calculate mass transfer coefficients for drag-reducing fluids. The essential steps in the calculation are as follows:

(1) Assume that in the mean velocity profile a logarithmic region is always present and described by the equation

$$v_z^+ = A \ln y^+ + B. \qquad (3)$$

Then, assuming the coefficient A is always constant and equal to its Newtonian value (2.5), calculate the value of B from either the equation of Edwards and Smith [13]

$$B = \frac{\langle v_z \rangle}{v^*} - 2.46 \ln \left[\frac{v^* Re}{\langle v_z \rangle} \right] + 4.82 \qquad (4)$$

or the equation of Arunachalem *et al.* [14]

$$B = B_{\mathrm{N}} \left(\frac{v_{\mathrm{N}}^*}{v^*} \right)^3. \qquad (5)$$

(2) Calculate the value of R^+ from the wall shear stress and y_2^+ from the equation

$$y_2^+ = \{R^+ - [R^{+2}(1 - 0.28A) - 4AR^+]^{1/2}\}/2 \quad (6)$$

(3) For the eddy viscosity expression of Spalding [15] calculate the values of v_z^+ corresponding to y_2^+ and R^+ from Spalding's expression for the mean velocity and evaluate the expression

$$\begin{aligned} C_{\mathrm{m}} = (C_{\mathrm{f}}/2)^{1/2}/\{(Sc - Sc_{\mathrm{tr}}) & \int_0^{v_{z0}^+} \\ & \times \mathrm{d}v_z^+/[1 + (Sc/Sc_{\mathrm{tr}})(\rho\varepsilon_{rz}/\mu)] + [Sc_{\mathrm{tr}}/(C_{\mathrm{f}}/2)^{1/2}] \\ & \times [4.07(C_{\mathrm{f}}/2)^{1/2} + 1] - 3.75\} \end{aligned} \qquad (7)$$

Different expressions for $\rho\varepsilon_{rz}/\mu$ were used in the intervals 0 to v_{z2}^+ and v_{z2}^+ to v_{z0}^+ as outlined previously [2].

(4) For the eddy viscosity correlations of Wasan *et al.* [16], Mizushina *et al.* [12] and van Driest [17], calculate the values of the constants in the various expressions as detailed by Edwards and Smith [13]. The dimensionless mass transfer coefficient is determined from:

$$C_{\mathrm{m}} = (C_{\mathrm{f}}/2)^{1/2} \Bigg/ \left\{ \int_0^{R+} \left[(1 - y^+/R^+) \Bigg/ \left(\frac{1}{Sc} + \frac{1}{Sc_{\mathrm{tr}}} \frac{\rho\varepsilon_{rz}}{\mu} \right) \right] \mathrm{d}y^+ - 3.75 \right\} \quad (8)$$

In order to evaluate the integral in the above expression, it is divided into three zones i.e. 0 to y_1^+, y_1^+ to y_2^+ and y_2^+ to R^+.

Tables 3–5 give comparisons of Sherwood numbers calculated from the various eddy viscosity expressions

Table 3. Mean percentage deviations between predicted and experimental Sherwood numbers for NaOH solutions

Eddy viscosity expression			
Spalding	Wasan *et al.*	Mizushina *et al.*	van Driest
21.9	9.8	14.3	5.9

and all the experimental mass transfer data for Polyox solutions reported in the previous section. The values in Tables 3–6 are mean percentage deviations between predicted and experimental Sherwood numbers. From these tables it can be seen that

(1) In general the agreement between theoretical predictions and experimental measurements is very good.

Table 4. Mean percentage deviations between predicted and experimental Sherwood numbers with the *B* coefficient calculated from Edwards and Smith

Polymer concn. (ppm)	Before/ after pumping	Eddy viscosity expression			
		Spalding	Wasan *et al.*	Mizushina *et al.*	van Driest
500	before	25.3	11.8	16.6	2.8
500	after	36.6	21.1	25.5	10.0
1000	before	15.8	7.8	11.1	11.1
1500	before	10.1	4.4	10.6	6.2
1500	after	33.8	19.2	24.5	7.3
2000	before	20.0	12.5	17.6	5.5
2500	before	16.7	11.1	16.7	3.9
2500	after	20.2	9.4	13.1	7.7
3000	before	8.5	4.4	9.1	8.3

Table 5. Mean percentage deviations between predicted and experimental Sherwood numbers with the *B* coefficient calculated from Arunachalem *et al.*

Polymer concn. (ppm)	Before/ after pumping	Eddy viscosity expression			
		Spalding	Wasan *et al.*	Mizushina *et al.*	van Driest
500	before	23.4	10.2	18.5	2.0
500	after	31.7	16.8	21.5	6.5
1000	before	15.4	6.6	11.0	9.7
1500	before	12.3	5.7	12.0	5.0
1500	after	31.1	16.9	22.3	5.5
2000	before	21.2	13.2	18.4	5.1
2500	before	18.4	12.1	17.7	5.2
2500	after	19.5	8.5	12.5	7.7
3000	before	10.0	5.3	10.1	7.6

Table 6. Mean percentage deviations between predicted and experimental Sherwood numbers averaged out over all the data for polymer solutions

B coefficient	Eddy viscosity expression			
	Spalding	Wasan *et al.*	Mizushina *et al.*	van Driest
Edwards *et al.*	20.2	11.0	15.8	7.0
Arunachalem *et al.*	19.8	10.3	15.7	6.1

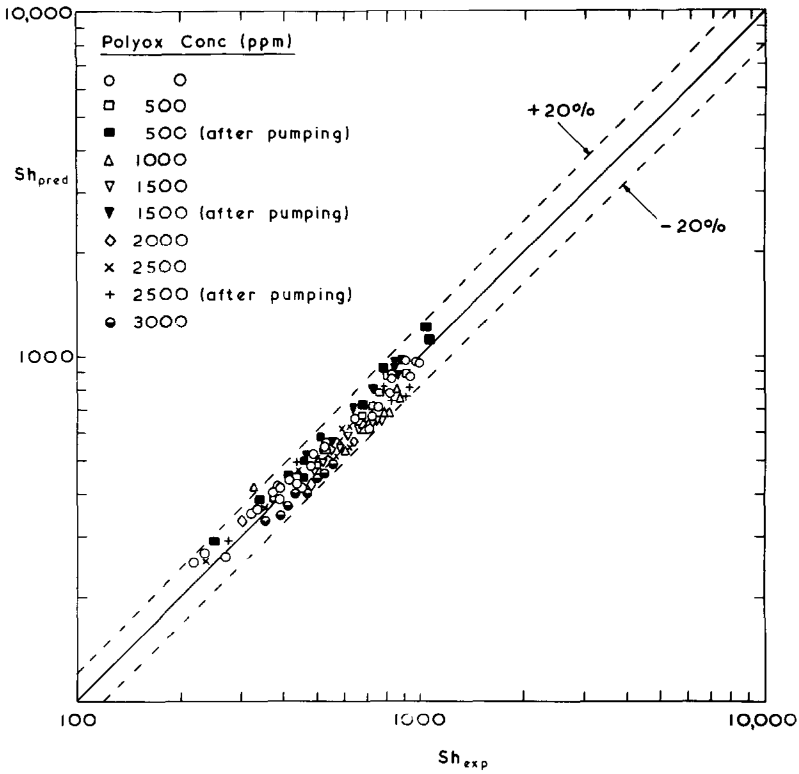


FIG. 8. Predicted versus experimental Sherwood numbers using the eddy viscosity correlation of van Driest with the *B* coefficient from Arunachalem *et al.*

(2) The eddy viscosity expression which gives clearly the best performance is that of van Driest. The previous investigation into heat transfer [2] concluded that the expressions of Mizushina *et al.* and van Driest gave the best predictions with generally comparable accuracy. The mass transfer data reported in the present investigation are more accurate than the heat transfer data previously analysed and are thus a more stringent test of the eddy viscosity expressions. It is interesting to note that the approach of Smith and Edwards [2] accounts not only for the drag-reducing effect but also the effect of flow with friction factors above the Nikuradse equation observed after shear degradation with the centrifugal pump. A previous investigation into the prediction of mean velocity profiles in turbulent drag-reducing pipe flow using the four eddy viscosity expressions discussed in the present paper concluded that there was little to choose between them [13]. Heat and mass transfer measurements, however, are a more sensitive test than mean velocity profiles.

(3) The two alternative methods of calculating the coefficient *B* from either equation (4) or (5) give results which are comparable in accuracy but slightly better predictions are obtained with the expression of Arunachalem *et al.*

Figure 8 gives a plot of experimental versus predicted Sherwood numbers for the NaOH solutions and those containing Polyox using the van Driest expression with the *B* coefficient calculated by Arunachalem *et al.* No systematic trends are evident. It is worth noting that the errors quoted for polymer solutions in Tables 4–6 and illustrated in Fig. 8 could have been reduced by smoothing out the experimental friction factor data rather than using the actual measured values in the calculations.

CONCLUSIONS

It was found that pumping Polyox solutions with a centrifugal pump caused rapid, irreversible shear degradation which considerably reduced the drag reducing properties of the solutions, decreased viscosities and increased diffusion coefficients. The drag reducing properties of Polyox solutions were also found to be considerably reduced by the presence of the electrolyte required for mass transfer measurements using the diffusion controlled electrolysis method. Four previously published Newtonian eddy viscosity correlations have been successfully adapted to predict mass transfer in drag-reducing turbulent pipe flow. This method predicts mass transfer rates directly from friction factor data without any reference to measured heat or mass transfer data. Over the range of experimental data examined, the eddy viscosity expression of van Driest [17] gave the best theoretical predictions. The agreement between experimental data and predictions is excellent with no systematic trends evident.

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PERTE DE CHARGE ET TRANSFERT MASSIQUE DANS DES SOLUTIONS DE POLYMERE REDUCTRICE DE FROTTEMENT EN ECOULEMENT TURBULENT DANS UN TUBE

Résumé—Une recherche extensive expérimentale a été conduite pour la perte de charge et le transfert massique dans des solutions aqueuses de Polyox (oxyde de polyéthylène) en écoulement turbulent dans un tube. La méthode de diffusion controlée éelectrolytique a été utilisée pour les mesures de transfert massique. On trouve que le pompage des solutions de Polyox par pompe centrifuge cause une dégradation rapide qui réduit considérablement les propriétés réductrices du frottement, diminue les viscosités et accroit les coefficients de diffusion. Les résultats expérimentaux de transfert massique à la fois pour les solutions fraiches et dégradées sont comparés avec les prévisions à partir des formules de viscosités turbulentes et un excellent accord est obtenu. La méthode de prévision ne dépend pas des données de transfert de chaleur et de masse mais seulement des données de coefficient de perte de charge.

DRUCKABFALL UND STOFFTRANSPORT IN VERDÜNNTEN POLYMERLÖSUNGEN BEI TURBULENTER, WIDERSTANDSVERMINDERTER ROHRSTRÖMUNG

Zusammenfassung—Umfangreiche experimentelle Untersuchungen hinsichtlich des Druckabfalls und des Stofftransports in einer wäßrigen Lösung von Polyox (Polyäthylenoxid) bei turbulenter Rohströmung wurden durchgeführt. Zur Messung des Stofftransports wurde die Methode der diffusionsbestimmten Elektrolyse verwendet. Es wurde festgestellt, daß durch Fördern der Polyox-Lösung mit einer Kreiselpumpe schnell eine Degradation eintrat, welche die reibungsvermindernden Eigenschaften der Lösung beträchtlich herabsetzte, die Viskositäten abnehmen und die Diffusions-Koeffizienten zunehmen ließ. Sowohl für frische als auch für gealterte Lösungen wurden experimentelle Stofftransportdaten mit Berechnungen, welchen Scheinreibungskorrelationen zugrundelagen, verglichen und eine gute Übereinstimmung festgestellt. Die Berechnungsmethode hängt nicht von gemessenen Werten des Wärme- oder Stofftransports ab, sondern nur von Widerstandsbeiwerten.

СОПРОТИВЛЕНИЕ И МАССОПЕРЕНОС ПРИ ТУРБУЛЕНТНОМ ТЕЧЕНИИ В ТРУБЕ РАЗБАВЛЕННЫХ ПОЛИМЕРНЫХ РАСТВОРОВ

Аннотация—Электрохимическим способом измерены потери напора и массоперенос в водных растворах полиокса (окиси полиэтилена). При нагнетании растворов центробежным насосом обнаружена деградация раствора настолько быстрая, что приводит к значительному ухудшению гидродинамических характеристик растворов, уменьшению вязкости и увеличению значений коэффициентов диффузии. Экспериментальные данные по массопереносу как для свежеприготовленных, так и уже использованных растворов хорошо согласуются с результатами расчетов по соотношениям для вихревой вязкости. Расчеты опираются не на измерения потоков тепла или массы, а только на данные о сопротивлении.