

# *Effect of drag reducing polymers on the rate of mass transfer in relation to their use as corrosion inhibitors in pipelines under turbulent flow conditions*

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Rates of mass transfer between a turbulently flowing fluid containing CMC drag reducing polymer and the wall of a tube were measured in the mass transfer entry region using the electrochemical technique. Variables studied were polymer concentration, surface roughness and solution flow rate. Carboxymethyl cellulose (CMC) was found to reduce the mass transfer coefficient by an amount ranging from 15 to 37% depending on the operating conditions. The percentage decrease in the mass transfer coefficient becomes greater with increasing CMC concentration and Reynolds number. CMC was found to reduce the rate of mass transfer at rough surfaces ( $e^+ > 3$ ) by an amount higher than that at a smooth surface. The possibility of using large polymers as drag reducers and corrosion inhibitors simultaneously in pipelines is indicated.

## Nomenclature

$I$	limiting current (A)
$Z$	number of electrons involved in the reaction
$F$	Faraday's constant
$A$	projected (geometrical) area of the cathode (cm <sup>2</sup> )
$K$	mass transfer coefficient (cm s <sup>-1</sup> )
$C$	concentration of ferricyanide ion (mole cm <sup>-3</sup> )
$e$	roughness height (cm)
$d$	tube diameter (cm)
$L$	length of transfer surface (cm)
$St$	Stanton number ( $K/V$ )
$Re$	Reynolds number ( $\rho Vd/u$ )
$Sc$	Schmidt number ( $\nu/D$ )
$e^+$	dimensionless height ( $eu^*/\nu$ )
$u^*$	friction velocity [ $V(f/2)^{1/2}$ ] (cm s <sup>-1</sup> )
$V$	solution velocity (cm s <sup>-1</sup> )
$f$	friction factor
$\nu$	kinematic viscosity (cm <sup>2</sup> s <sup>-1</sup> )
$u$	viscosity (poise)
$\rho$	density (g cm <sup>-3</sup> )
$D$	diffusivity (cm <sup>2</sup> s <sup>-1</sup> )

## 1. Introduction

Previous studies [1-11] of drag reducing polymers in solutions under turbulent flow have revealed the fact that a substantial decrease in the rate of mass transfer takes place in such solutions owing to the ability of polymer molecules to damp small-scale, high-frequency eddies prevailing in the buffer layer of the hydrodynamic boundary layer. This finding led to the idea of using drag reducing polymers to inhibit diffusion controlled corrosion in pipelines carrying turbulently flowing fluids such as water and oil [12, 13]. In this case the drag reducing polymers would act in two ways to cut down the pumping power requirement and the rate of corrosion. Diffusion controlled corrosion occurs frequently in practice when the rate of corrosion is determined either by the rate of dissolved oxygen diffusion to the metal surface or by the rate of removal of the anodic corrosion products from the metal surface [14]. In previous studies [12, 13], the effect of polyethylene oxide polymer (polyox) on the rate of diffusion con-

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trolled corrosion was examined, and inhibition efficiencies up to 80% were obtained. The object of the present work is to examine the effect of carboxymethyl cellulose (CMC) on the rate of mass transfer in smooth and rough tubes in relation to its possible use as a corrosion inhibitor in pipelines operating under turbulent flow conditions. Although the drag reducing ability of CMC is less than other polymers, e.g. polyox and separan, its resistance to mechanical (shear) degradation is superior [15]. Surface roughness may develop naturally in pipelines due to corrosion and scale formation or may be present deliberately to enhance heat transfer [16].

The present work was carried out by measuring the limiting current of the cathodic reduction of potassium ferricyanide in alkaline solution. This system has the advantage over the anodic dissolution of metals (e.g.  $\text{Cu-H}_3\text{PO}_4$ ) that the rough surface remains unaltered during the experiment.

## 2. Experimental technique

The experimental apparatus used is shown in Fig. 1. It consisted of a 30 dm<sup>3</sup> plastic storage

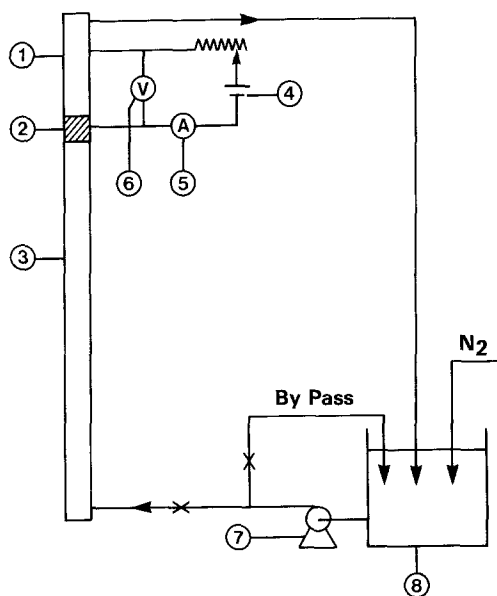


Fig. 1. Experimental set-up: 1. outlet section (anode); 2. working section (cathode); 3. entrance section; 4. 6 V d.c. power supply with a voltage regulator; 5. multirange ammeter; 6. high impedance voltmeter; 7. centrifugal pump; 8. 30 dm<sup>3</sup> plastic storage tank.

tank, a stainless steel centrifugal pump and a vertical tubular cell. The electrolytic cell consisted of three sections, the entrance section, the working section and the outlet section. The three sections were made of a nickel-plated copper tube with a diameter of 2.4 cm. The entrance section, which preceded the working section, was 235 cm (99  $d$ ) in length, this length is sufficient to give a fully developed flow at the working section [16]. The working section was 2.4 cm (1  $d$ ) in length. The outlet section was 48 cm (20  $d$ ) in length and was placed downstream from the working section. The three sections were connected to form one straight tube using a threaded plastic sleeve as shown in Fig. 2. The working section was isolated electrically from the inlet and outlet sections by plastic washers (gaskets) which also served to prevent solution leakage at the connections between the three sections. The working section served as the cathode of the electrolytic cell while the outlet section served as the anode. The electrical circuit consisted of a 6 V d.c. power supply with a voltage regulator connected in series with a multirange ammeter and the cell. A voltmeter was connected in parallel with the cell.

One smooth and two rough cathodes were used in the present study. Surface roughness was effected by cutting threads in the inner surface of a copper tube followed by electroless nickel plating. Measurement of the dimensions of surface

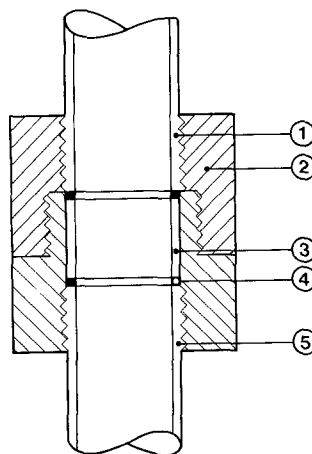


Fig. 2. Details of the working section: 1. outlet section; 2. threaded plastic sleeve; 3. working section; 4. plastic washer (gasket); 5. entrance section.

Table 1. Properties of rough surfaces

Degree of roughness	Pitch (mm)	Peak-to-valley height (mm)	e/d
$R_1$	0.82	0.141	$5.88 \times 10^{-3}$
$R_2$	0.82	0.188	$7.83 \times 10^{-3}$

roughness was carried out on the nickel-plated surface. Table 1 shows the characteristics of the two rough cathodes used in the present study.

The electrolyte used was composed of a blank solution and a few ppm of carboxymethyl cellulose sodium salt (CMC-7H, a product of Hercules Chemical Corporation). The blank solution consisted of  $0.025 \text{ mol dm}^{-3}$  potassium ferricyanide,  $0.025 \text{ mol dm}^{-3}$  potassium ferrocyanide and 1N sodium hydroxide. The solution was prepared using distilled water and AR chemicals. Polymer solutions were prepared by digesting the required weight of CMC in water overnight until sufficient polymer swelling took place and then the polymer solution was mixed with a solution containing the other chemicals to obtain the required composition. Three CMC concentrations were used in the present study 100, 200 and 300 ppm. Rheological measurements have shown that the three solutions are Newtonian. Before and during each run,

nitrogen gas was bubbled in the storage tank to remove dissolved oxygen which may interfere with the cathodic reduction of potassium ferricyanide solution. Cathode pretreatment was similar to that of Eisenberg *et al.* [17]. Solution flow rate was controlled using a bypass and was measured using a graduated cylinder and stop-watch. The viscosity and density of each solution were measured by an Ostwald viscometer and a density bottle, respectively. The diffusivity of ferricyanide ions was calculated using the formula of Gordon *et al.* [18]. Limiting currents were determined under different conditions from polarization curves. These were constructed by increasing the cell current stepwise and measuring the corresponding steady-state cell voltage. Every experiment was repeated twice. The mass transfer coefficient was calculated from the limiting current using the equation:

$$K = \frac{I}{ZFAC} \quad (1)$$

In cases of rough surfaces, the projected area rather than the true area was used in calculating  $K$ . The temperature was maintained at  $25^\circ \text{C}$ .

### 3. Results and discussions

Polarization curves with well-defined limiting

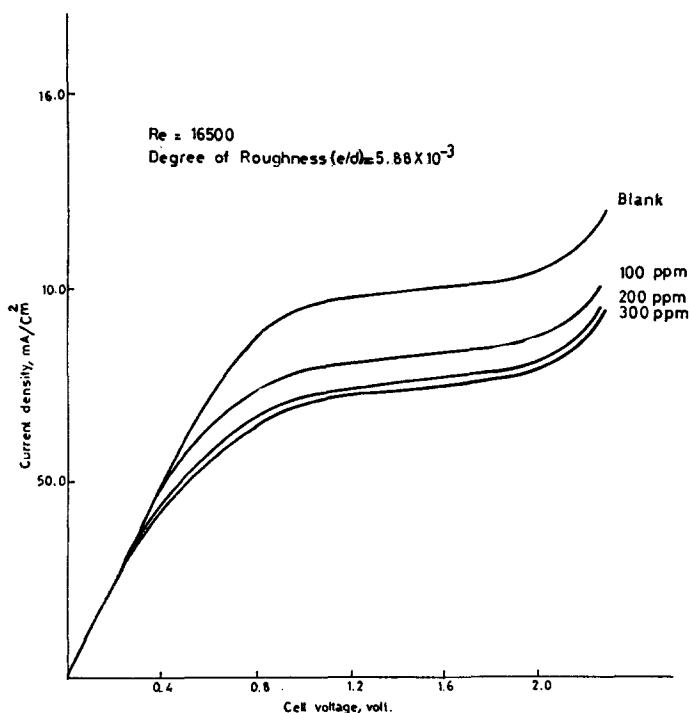


Fig. 3. Typical polarization curves obtained at different CMC concentrations.

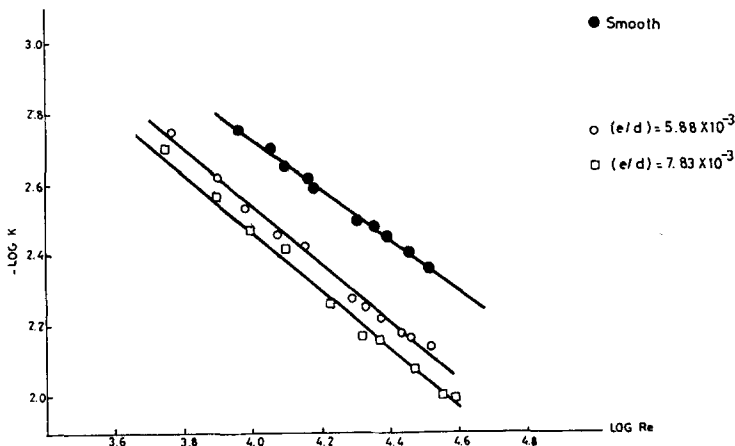


Fig. 4. Log  $K$  versus log  $Re$  for different degrees of roughness.

current plateaus were obtained under different conditions as shown in Fig. 3. Figure 4 shows that under present conditions surface roughness increases the rate of mass transfer up to a maximum of 115% in polymer-free solution. Within the range of  $Re$  used in the present study the roughness elements for rough surface  $R_1$  ( $e/d = 5.88$ ) and rough surface  $R_2$  ( $e/d = 7.83$ ) extend beyond the laminar sublayer of the hydrodynamic boundary layer ( $e^+ > 3$ ) where they induce the formation of strong eddies which penetrate the diffusion layer and enhance the rate of mass transfer [19]. Also surface roughness con-

tributes to increasing the rate of mass transfer through increasing the effective diffusional area [20].

Figure 5 shows that the results of mass transfer between the blank solution and the smooth surface fit Hanratty's equation [21] which correlates mass transfer to a tube wall in the mass transfer entry region with an average deviation of 5.6%

$$St = 0.276 Sc^{-0.66} Re^{-0.417} (L/d)^{-0.33} \quad (2)$$

This agreement testifies to the soundness of the present experimental technique.

Figures 6–8 show that CMC reduces the mass transfer coefficient by an amount depending on  $Re$ , polymer concentration and surface roughness. Table 2 shows that the percentage decrease in the mass transfer coefficient ranges from 11 to 39%. The percentage reduction in the mass transfer coefficient increases with increasing  $Re$ , probably because of the increase in the degree of expansion of the polymer molecules. The higher the degree of expansion of the polymer molecules, the higher their ability to damp turbulent eddies [22]. Table 2 shows that for the two rough surfaces  $R_1$  and  $R_2$  where the roughness elements extend beyond the laminar sublayer ( $e^+ > 3$ ), the percentage reduction in the mass transfer coefficient is higher than that at the smooth surface. This may be explained as follows: in the presence of a drag reducing polymer, the thickness of the laminar sublayer and the diffusion layer increases owing to the damping of the small-scale, high-frequency eddies existing outside the laminar sublayer. Accordingly a larger portion of the roughness

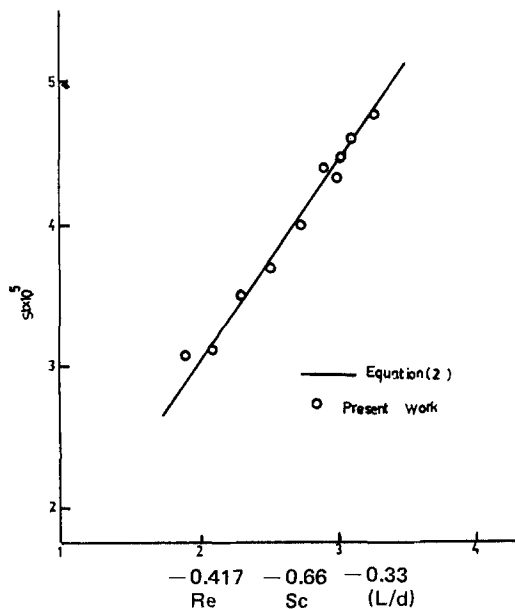


Fig. 5. Overall mass transfer correlation at a smooth surface.

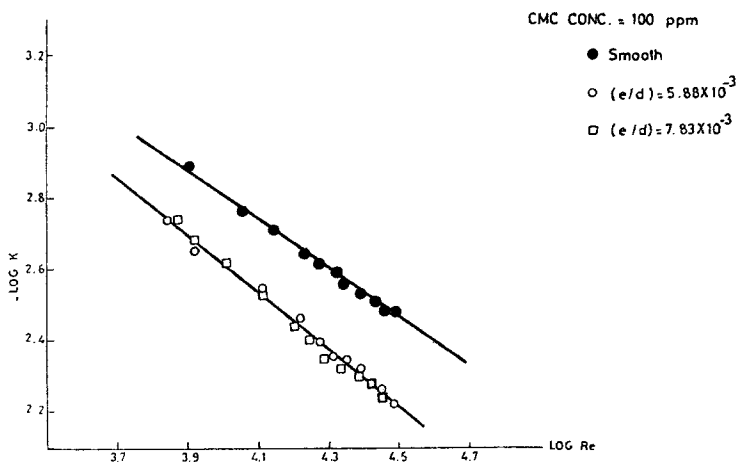


Fig. 6. Log  $K$  versus log  $Re$  for different degrees of surface roughness in CMC solution.

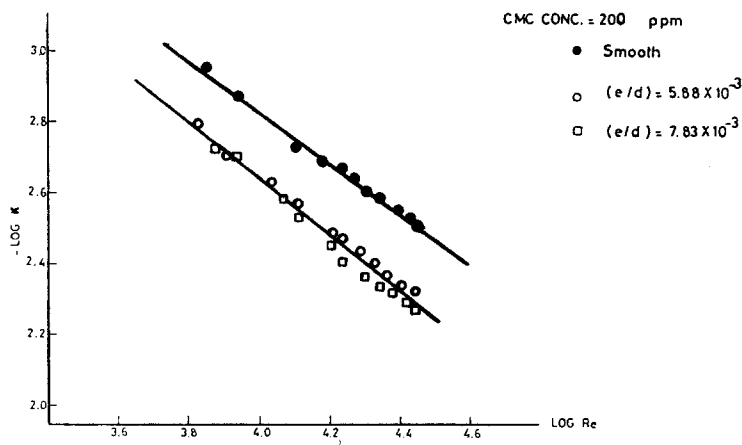


Fig. 7. Log  $K$  versus log  $Re$  for different degrees of roughness in CMC solution.

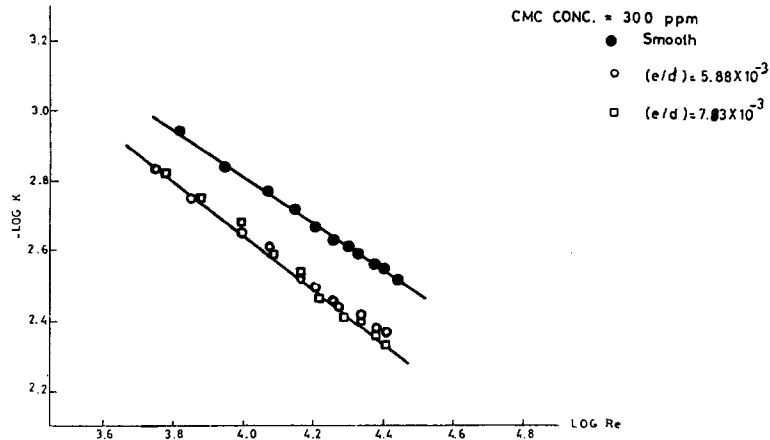


Fig. 8. Log  $K$  versus log  $Re$  for different degrees of roughness in CMC solution.

Table 2. Effect of degree of roughness on the percentage reduction in the mass transfer coefficient at different Reynolds number and polymer concentration

Degree of roughness	Reynolds number	Percentage		
		100 ppm CMC	200 ppm CMC	300 ppm CMC
Smooth	30 000	18	21	23
Smooth	20 000	17.5	20	22
Smooth	15 000	16	18	20
Smooth	10 000	15	17	18
$R_1$	30 000	23	32	34
$R_1$	20 000	19	30	33
$R_1$	15 000	18	28	32
$R_1$	10 000	16.5	26	29
$R_2$	30 000	29.5	29.5	37
$R_2$	20 000	26	28	35
$R_2$	15 000	24.5	25.5	34
$R_2$	10 000	23.5	24.5	33

elements becomes submerged in the diffusion layer with a consequent decrease in the effective diffusional area and the ability of the protrusions to induce the formation of eddies [19]. Consequently, the rate of mass transfer decreases to a greater degree than at the smooth surface whose diffusional area is unaffected by the presence of polymer. Another possible explanation for the higher percentage reduction in mass transfer coefficient at rough surfaces compared to smooth surfaces is that: since only small-scale, high-frequency eddies are damped by polymer molecules [23], it is probable that the proportion of such eddies in the turbulence spectrum prevailing at rough surfaces is higher than that at smooth surfaces. This assumption seems plausible in view of the ability of the roughness elements to induce the formation of new eddies; however, experimental study of the turbulence structure at a rough surface compared with a smooth surface is needed to substantiate this assumption.

Debrule and Sabersky [24] studied rates of heat transfer between a rough tube and a drag reducing fluid; they found that the heat transfer coefficient is reduced more drastically at the rough surface than at the smooth one. However, these authors found that at relatively high  $Re$  values, the polymer loses its effectiveness at rough surfaces. They attributed this to mechanical degradation caused by the high shear stress at the rough wall. Spangler [25] showed that the loss of

effectiveness was not due to polymer degradation since the friction was reduced in smooth pipe sections both upstream and downstream of the roughened area.

For the quantitative prediction of the percentage reduction in mass transfer between smooth tubes and solutions containing CMC, an overall mass transfer correlation was envisaged in terms of the dimensionless groups  $St$ ,  $Re$  and  $Sc$ . Figure 9 shows that the data can be represented with the equation:

$$St = 0.472 Sc^{-0.66} Re^{-0.245} (L/d)^{-0.33} \quad (3)$$

with an average deviation of 4.4%.

In conclusion, the present study confirms the possibility of using large polymers as corrosion inhibitors and drag reducers simultaneously in smooth and rough pipelines operating under turbulent flow conditions with the advantage of increasing the life span of the pipeline and reducing the pumping power requirement. Typical examples of where polymers can be used as drag reducers and corrosion inhibitors are in the transport of water and oil through long pipelines and chemical industries where corrosive fluids are handled. Polymers can also be used in recirculating cooling systems but only with caution since the deleterious effect of the polymer on the rate of heat transfer may outweigh the benefits gained from drag reduction and corrosion inhibition.

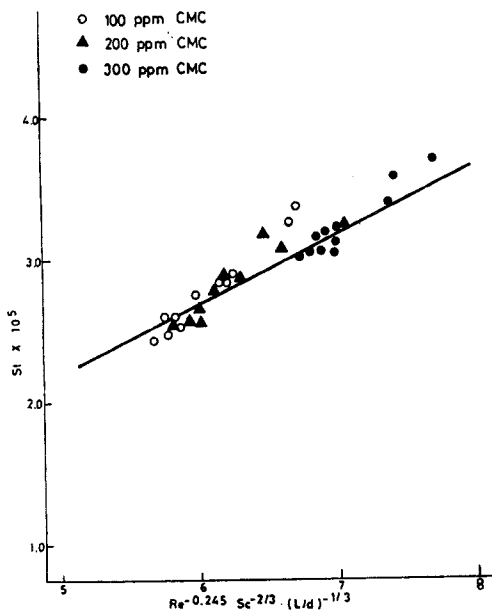


Fig. 9. Overall correlation of mass transfer between smooth surfaces and CMC solutions.

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