Simulation of Biocorrosion in Pipe Flow Using an Electrochemical Glass Cell Bioreactor with a Rotating Cylinder Coupon

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Abstract

Microbiologically influenced corrosion (MIC) is a growing problem in the oil and gas industry that results in huge financial losses each year worldwide. Reservoir souring, equipment and pipeline failures due to MIC pitting attacks are of great concerns in field operations. A group of bacteria known as sulfate reducing bacteria (SRB) are often the culprits. Currently, the basic understanding of SRB biofilm growth and MIC under flow conditions is still surprising lacking. Mass transfer plays an important role in MIC and fluid flow is related to mass transfer and fluid shear. Fluid shear impacts biofilm attachment and growth that are directly linked to MIC. This work aimed at studying mass transfer and flow effects on MIC due to SRB. It is very inconvenient to use a pipe flow system to study MIC because of the very high requirement on pump flow rates. An electrochemical glass cell bioreactors with a rotating cylinder coupon was used to simulate pipe flows. The ATCC 7757 strain of *Desulfovibrio desulfuricans* (a common SRB) was used in this work. The carbon steel coupon's rotation speed could be mathematically correlated with the average linear velocity in pipe flow. The experimental results from this work help understand MIC behavior under stagnant and flow conditions. They may also provide criteria for using fluid shear as a potential non-biocidal mitigation method.

Introduction

Microbiologically influenced corrosion (MIC) causes significant financial losses in production cutback and equipment maintenance in the oil and gas industry (Costerton and Boivin, 1991).

Most reports on MIC on the lab scale were done under non-flow conditions in anaerobic vials. However, MIC occurs not only in stagnant conditions, but also on surfaces with liquid flow. Lee and Characklis (1993) observed MIC at linear velocities of about 0.35 m/s on AISI 1018 mild steel. Mass transfer limited conventional corrosion can be accelerated by liquid flow (Silverman, 1984). In MIC research involving moving fluids, hydrodynamics and nutrient availability are two key factors influencing the biofilm growth. Hydrodynamic conditions can facilitate mass transfer but may also exert excessive shear that causes inhibition of cell adhesion and the detachment of biofilms (Stoodley et al., 1999). By using a recirculation loop with a vessel, Dunsmore et al. (2002) reported that the structure and material properties of SRB were influenced by the fluid shear.

It is difficult to use a pipe flow system to study MIC because a large pump flow rate is needed to achieve the needed linear velocity on a coupon surface. A glass cell with a rotating cylinder coupon equipped with a potentiostat can be used in the lab to study the steel corrosion behavior. The shear stress on the

surface of rotating cylindrical coupon can be calculated using following equation (Silverman, 1984):

$$\tau_{cyl} = 0.079\,\mathrm{Re}^{-0.30}\,\rho(\omega r)^2 \qquad (1)$$

By assuming the surface to be hydraulically smooth for both pipe and rotating cylinder, Silverman (1988) also proposed an equation to correlate the rotation speed of the cylindrical coupon in glass cell with the average linear velocity in pipe flow:

$$u_{cyl} = 0.1185\left[\left(\frac{\mu}{\rho}\right)^{-0.25}\left(\frac{d_{cyl}^{3/7}}{d_{pipe}^{5/28}}\right)Sc^{-0.0857}\right]u_{pipe}^{5/4} \qquad (2)$$

Figure 1 shows the correlation between cylinder rotation rate and pipe velocity. The viscosity, density, Schmidt number and diameter of the cylinder coupon used in calculation are 0.01 poise, 1 g/cm^3, 1000, and 1.2 cm, respectively.

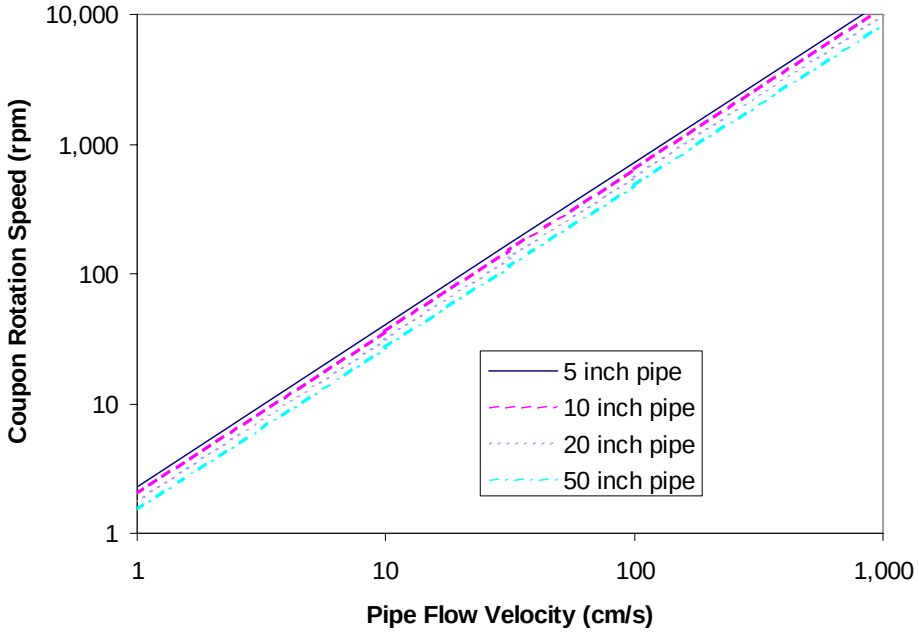

Figure 1. Correlation between cylinder rotation rate and linear velocity in pipe flow calculated from Equations (2).

The MIC research group at Ohio University previously showed that mild agitation could promote the planktonic SRB growth while a threshold flow rate may exist corresponding to maximum MIC (Wen et al., 2006). This work presents some information on the SRB biofilms under flow conditions.

Experimental Procedure

The ATCC 7757 strain of *Desulfovibrio desulfuricans* was used in this work. Laboratory experiments were carried out in a glass cell bioreactor with a rotating cylinder coupon of C1018 carbon steel (Figure 2). The composition of culture medium for SRB and the text matrix are shown on Tables 1 and 2, respectively. Cysteine was used as an oxygen scavenger. To inhibit the suspended FeS precipitation on the coupon surface, a special chemical was used. The coupon was polished successively by sand paper with 200, 400 and 600 grits. The bioreactor was autoclaved prior to inoculation. The culture medium was inoculated using a SRB culture from an anaerobic vial after deoxygenation. To reduce oxygen contamination, a small positive overhead pressure was maintained by feeding filtered nitrogen to the glass cell.

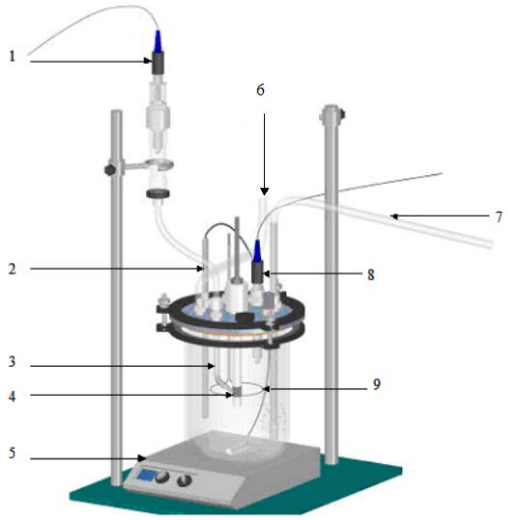

Figure 2. Schematic of an electrochemical glass cell bioreactor: (1) Reference electrode, (2) Temperature probe, (3) Luggin capillary, (4) Working electrode, (5) Hot plate, (6) Gas output, (7) Bubbler for gas, (8) pH electrode, and (9) Counter electrode. (Figure courtesy of Danniel Mossier at Ohio University, 2004.)

Table 1. Composition of ATCC 1249 medium for SRB

Component I	$MgSO_4$	2.0 g
	Sodium Citrate	5.0 g
	$CaSO_4$	1.0 g
	NH_4Cl	1.0 g
	Distilled water	400 ml
Component II	K_2HPO_4	0.5 g
	Distilled water	200 ml
Component III	Sodium Lactate	3.5 g
	Yeast Extract	1.0 g
	Distilled water	400 ml
Component IV	$Fe(NH_4)_2(SO_4)_2$	0.127 g

Table 2. Test Matrix

Test strain	*Desulfovibrio desulfuricans* (ATCC 7757)
Test medium	Modified ATCC 1249 medium
Oxygen scavenger (cysteine) (g/L)	0.5
Coupon Material	UNS C1018
Temperature (ºC)	37
pH	7.0±0.1
Rotation speed (rpm)	0, 1000, 3000

To prepare the SRB biofilm on a C1018 steel coupon for observation under a scanning electron microscopy (SEM), the coupon's exposed surface was fixed in 2.5% (wt) glutaraldehyde for 8 hours and washed with a graded series (30%, 50%, 70%, 100% v/v) of ethanol for dehydration. The coupon surface was subsequently critical point dried and coated with a special gold alloy.

Results

SEM biofilm images on coupon surface at different rotation rates were shown below. Peanut-shaped sessile SRB were clearly visible on coupon surfaces that were obtained for 5-day tests using stagnant condition and rotating rate of 1000 rpm. The cells were hard to detect at rotating rate of 3000 rpm. This result is consistent with the previous results that mild agitation could promote the planktonic SRB growth while a threshold flow rate may exist corresponding to maximum MIC (Wen et al., 2006). At 3000 rpm, the biofilm formation on the coupon surface was inhibited, which could be correlated to pipe velocity of 3.5 m/s for 10" pipeline based on Silverman (1988) correlation.

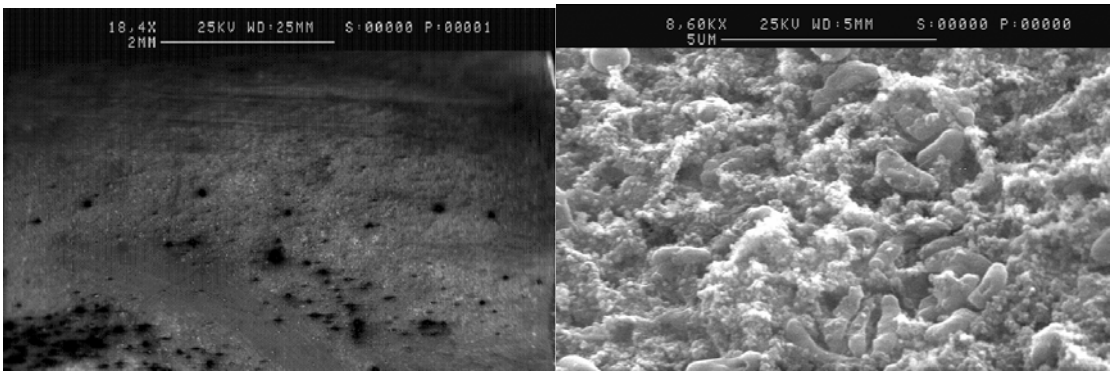

Figure 3. SEM biofilm images on coupon surface for 0 rpm rotation rate.

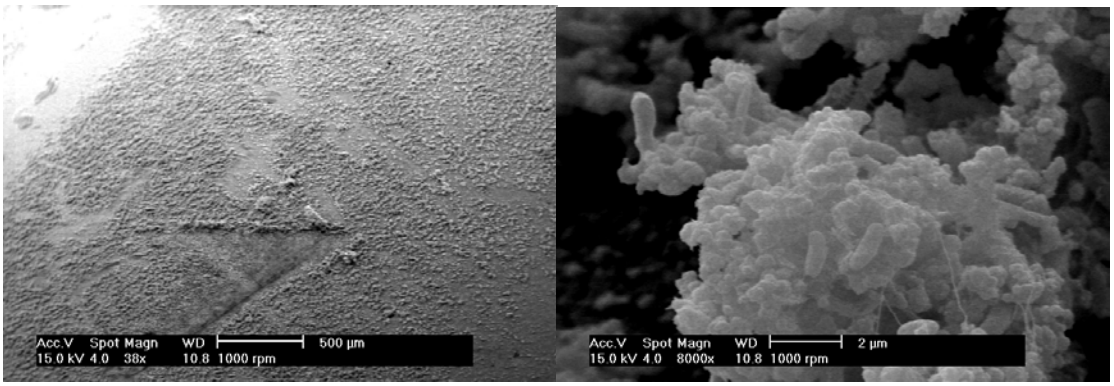

Figure 4. SEM biofilm images on coupon surface for 1000 rpm rotation rate.

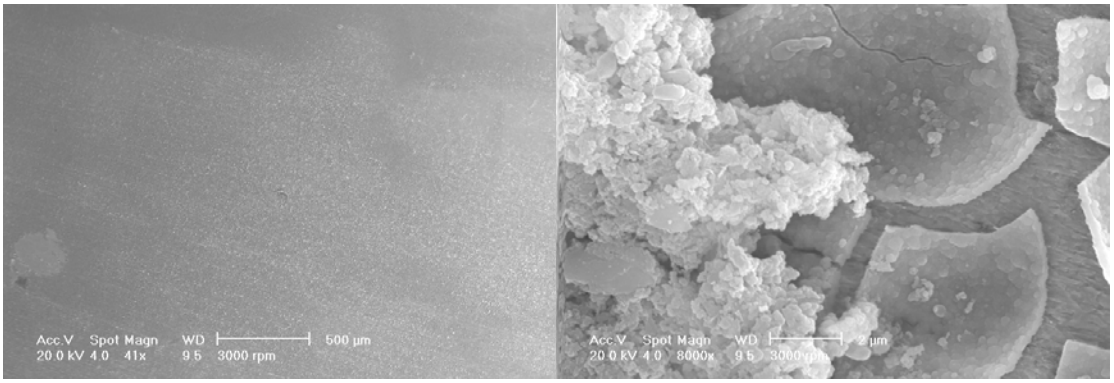

Figure 5. SEM biofilm images on coupon surface for 1000 rpm rotation rate.

Conclusions

Fluid flow rate was found to impact sessile SRB growth on the coupon surface. It was shown that at a high flow rate, the SRB biofilm could not establish on the coupon surface. This points to a potential MIC mitigation method without chemical treatment.

References

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