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On-Line Side-Stream Monitoring of Biofouling

*Frank L. Roe, Eric Wentland, Nick Zelter, Bryan Warwood,
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I. INTRODUCTION

Bacteria will adhere to and grow on most surfaces in flowing aquatic environments. The deposits which accumulate are called biofilms.^{1,2} Biofouling, which is the undesirable accumulation of biofilm, imposes a significant cost on society. These costs include increased energy needs in pumping systems, decreased efficiency in heat exchangers, early equipment failure due to biocorrosion, decreased life expectancy of equipment due to harsh biofouling control procedures, aesthetic degradation of products, and increased health risks.

Biofilms consist of cells growing in a matrix of a viscous permeable polysaccharide secretion or biopolymer and often include embedded inorganic particles such as sediments, scale deposits, or corrosion deposits. Biofilms continuously change in thickness, surface distribution, microbial populations, and chemical composition, and respond to changes in environmental factors such as water temperature, water chemistry, and surface conditions. This dynamic nature of biofilms makes it difficult to measure and predict the course of biofouling, and thus often reduces the effectiveness of treatment strategies. Site-specific continuous monitoring of biofouling rates and extent of fouling is essential to verify mathematical models and to fine tune procedures for efficient and

effective treatment of biofouling. A variety of different monitors for biofouling are reported in the literature.^{3,4}

The purpose of this study was to evaluate on-line side-stream monitoring of biofilm development using an instrumented annular reactor and compare it with biofilm development in a tubular system. Continuously collected data — torque and light transmittance in the annular reactor, and heat transfer resistance (HTR) and pressure drop (PD) in the tubular system — were complemented by measuring attached mass for both systems at the end of each experiment. The goal was to show that a suitably instrumented annular reactor could predict biofouling development in an industrially relevant tubular system.

The annular reactor⁵⁻⁸ is a side-stream reactor which can be used to monitor accumulation of biofilm in any fluid flow system. It accepts a side-stream portion of the process water and measures fouling potential at a surface employing a user-selected shear stress. It has commonly been used for laboratory studies of biofouling, but is presented here as a potential device for continuous monitoring in field situations. It is an ideal platform for mounting biofouling probes to assess biofilm accumulation; it is small, simple, versatile, and rugged. Sensors that have been suggested include torque, light transmittance, HTR, and a variety of specific ion probes. All of these can be monitored in real time using a computer data-acquisition system. We report here on use of a torque monitor and a light transmittance probe with the annular reactor for continuous monitoring of biofouling.

We chose torque to study in detail for a variety of reasons, the most compelling being that it was an average measure of fouling, rather than a localized measure. Localized variables such as light transmittance of the biofilm or near-surface dissolved-oxygen concentration would be expected to show significant spatial variability. This variability can be valuable in other contexts; however, we felt that there was less chance for false-positive or -negative indications of fouling with torque. Another advantage is that the torque monitor, once calibrated, maintains its accuracy over long periods. Chemical sensors have an added drawback in that the measured signals drift and the probes are difficult to calibrate *in situ*. Optical sensors, which have an initial limited range of sensitivity, are also sensitive to qualitative changes in the biofilm and process water, further reducing their usefulness.

II. EXPERIMENTAL

A. Equipment

1. Loop System

The simulated industrial system consisted of a tubular recycle loop shown in Figure 1. It was fabricated from 0.5-in.-diameter stainless steel tubing.

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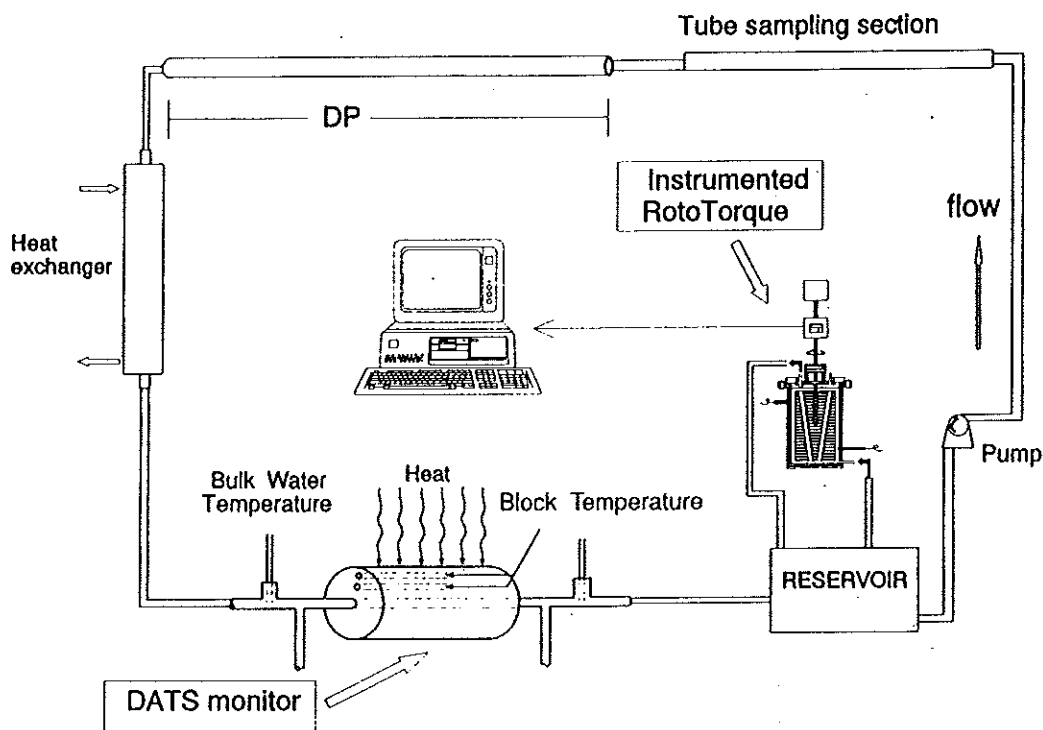


FIGURE 1. Instrumented annular reactor installed side-stream to a recycle loop system.

A centrifugal pump took water from the mixing tank and passed it through the loop at a flow rate controlled by a motorized valve. HTR was measured in a simulated heat exchanger located on one section of the loop. PD was measured across another section of the loop. From a third section of the loop, 5-in. sections of pipe were cut for mass accumulation measurements.

The mixing tank was operated as a continuous-flow stirred-tank reactor with a total volume of approximately 110 l. Dilution water (56.7 l/h) and nutrients (284 mg/h glucose plus 7 mg/h nitrogen and 14 mg/h phosphorous) were fed to the mixing tank using a tubing pump. Temperature in the mixing tank was controlled at $24 \pm 2^\circ\text{C}$.

2. Annular Reactors

The annular reactors were fabricated from PVC (see Figure 2). Each consisted of a stationary outer drum and a rotating inner cylinder. A port located in the bottom housing allowed introduction of fluids, while removal of fluids took place at the top.

Water from the mixing tank was recirculated through two annular reactors operated independently and in parallel.

Data acquisition system for collection and processing of sensor outputs. Processes data for correlation of process, fouling, and corrosion events.

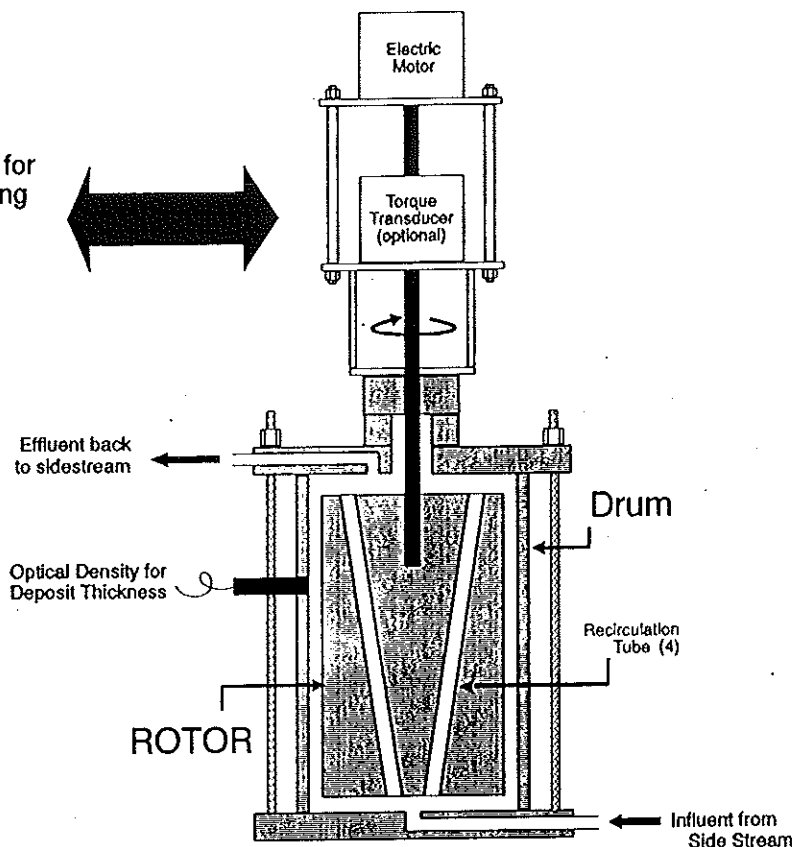


FIGURE 2. Annular reactor system.

Torque was measured using a General Thermodynamics torque monitor.

3. Data Acquisition

Computer data-acquisition systems were used to collect continuous torque, HTR, differential pressure (DP), loop flow rate, and loop temperature data.

For annular reactor torque, signal conditioning was accomplished using the circuit in Figure 3. A 5-V supply provided the driving voltage for the bridge circuit which consisted of the torque-proportional potentiometer in the torque monitor and a zeroing potentiometer in the signal conditioner. Output from the signal conditioner was fed to a Metrabyte® DAS-8 A/D board in a Zenith® 386 25-MHz microcomputer. LabTech® Notebook data-acquisition software was used to collect data from the torque monitors.

Instrumentation for the light transmittance probe is shown in Figure 4. Modulated light from an infrared light-emitting diode (IRLED) passes through a fiber optics cable embedded in the outer drum wall of the

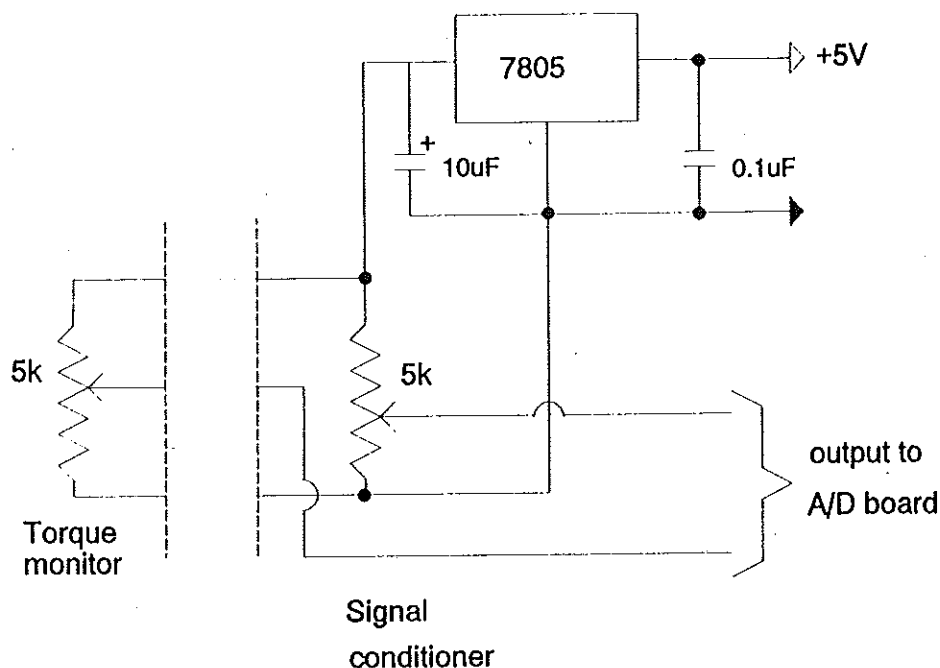


FIGURE 3. Torque monitor signal conditioner.

annular reactor, through the biofilm on the outer wall, through the biofilm on the inner wall, and is reflected back along the same path to the detector. The signal conditioner detects light of the same phase as that emitted by the IRLLED, converts it to a frequency proportional to intensity, and then finally converts it to a voltage using a frequency-to-voltage converter.

For the tubular recycle system, HTR, PD, flow rate, and water temperature were automatically logged to a Bridger Scientific DATS Fouling Monitor System. Periodically, data was dumped from the DATS to the microcomputer using Bridger Scientific DATS-specific software.

All computer-collected data were eventually merged and analyzed using Borland's® Quattro Pro spreadsheet software.

4. Manual Measurements

Biofilm mass was manually measured at the end of each experiment. For the annular reactor, the inner rotor surface was allowed to drain for 5 min, and then was scraped with a rubber spatula into an aluminum boat. The residue was dried at 60°C for 24 h and weighed. For the tubular system, three 10-cm sections were cut from the loop, drained for 5 min, dried at 60°C for 24 h, and weighed. The tube sections were then cleaned with a bristle brush, dried as before, and reweighed. The difference between the two weights was the dry mass of the deposits on the tube sections.

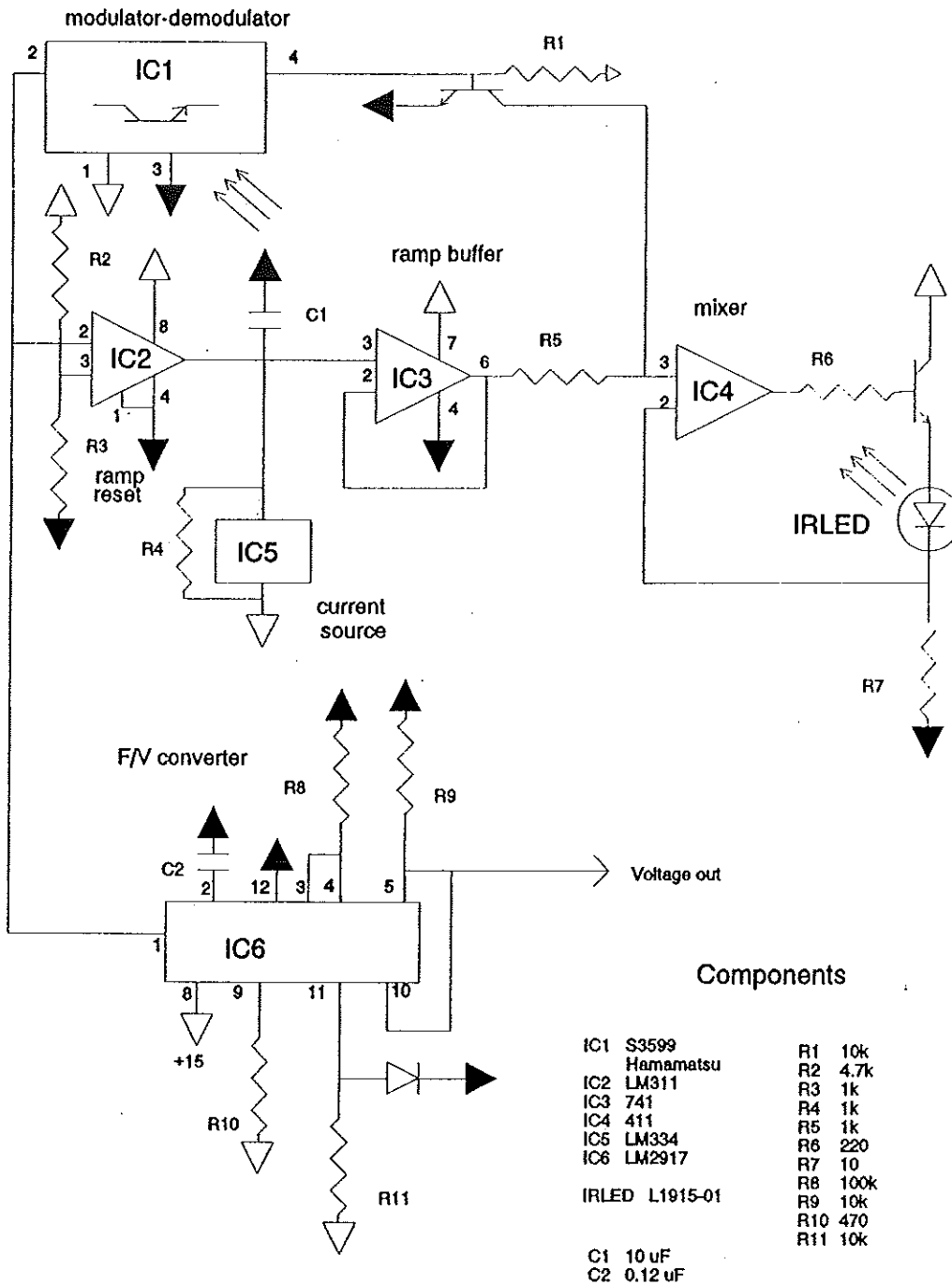


FIGURE 4. Light transmittance probe electronics.

B. Procedures

Shear stresses in the annular reactors and in the loop system were approximately matched at the start of an experiment. First, torque was measured for an annular reactor rotational speed of 175 rpm. Then shear stress was calculated at the inner cylinder surface using Equation 1:

$$\tau_{ar} = \frac{T}{R \cdot A} \quad (1)$$

where τ_{ar} = shear stress at the cylinder wall ($ML^{-1}T^{-2}$)
 A = surface area of the cylinder (L^2)
 T = torque (ML^2T^{-2})
 R = cylinder radius (L)

Shear stress in the pipe was then matched to shear stress in the annular reactor by adjusting the fluid velocity using the relationship in Equation 2,

$$\tau_{ar} = \tau_{pipe} = f\rho \frac{V^2}{8} \quad (2)$$

also using the Blasius equation:

$$f = \frac{0.316}{Re^{0.25}} \quad (3)$$

and the Reynolds number equation:

$$Re = \frac{Vd}{\nu} \quad (4)$$

If Equations 3 and 4 are substituted into Equation 2, then

$$\tau_{pipe} = \frac{0.316}{8 \left(\frac{Vd}{\nu} \right)^{0.25}} \rho V^2 \quad (5)$$

or

$$\tau_{pipe} = 0.0395 \rho^{1.75} \nu^{0.25} d^{-0.25} \quad (6)$$

where f = friction factor (dimensionless)
 Re = Reynolds number (dimensionless)
 V = velocity (LT^{-1})
 d = tube diameter (L)
 ν = kinematic viscosity (L^2T^{-1})
 ρ = density of water (ML^{-3})
 τ_{pipe} = shear stress at pipe wall ($ML^{-1}T^{-2}$)

Since both ρ and ν are temperature dependent, the appropriate values at 23.9°C ($\nu = 9.20E - 7 \text{ m}^2/\text{s}$ and $\rho = 997.5 \text{ kg/m}^3$) are substituted into Equation 5.

Rearranging and solving for V resulted in the desired pipe flow velocity of 0.91 m/s. Due to an error in calculation, the actual velocity used was 1.18 m/s — 30% larger than the desired velocity. Residence times in each of the two subsystems were under 15 s. As a consequence, both systems were exposed to the same water quality throughout each experiment.

The majority of data was obtained over a period of several months. The system was run continuously over this period after inoculating with a single sample of an undefined mixed population. Between experiments the surfaces of interest — annular reactors, HTR section, DP section, mass accumulation section — were cleaned with a fiber brush until measured variables returned to baseline values. This procedure insured that rapid attachment and growth would occur.

III. RESULTS

Results are presented in two parts; the first part compares data measured at the end of each experiment, while the second part compares data collected continuously during each experiment. Each experiment lasted approximately 7 d.

A. End-of-Run Comparisons

A plot of annular reactor dry biofilm mass vs. tube dry biofilm mass on a per unit area basis is shown in Figure 5. The slope of the plot of annular reactor mass vs. tube mass was 0.69 and the r^2 is 0.94.

End-of-run HTR, DP, and torque (Figures 6 and 7), on the other hand, were not well correlated with mass accumulation, nor were HTR or DP well correlated with torque (Figure 8).

B. Continuous Annular Reactor and Loop System Comparisons

A graph of a typical run is seen in Figure 9. HTR rose rapidly, fell, and then started to rise again, often with considerable fluctuation. DP rose rapidly, but not as fast as HTR. It eventually leveled off or continued rising at a slower rate. Torque showed a constant gradual rise throughout the experiment.

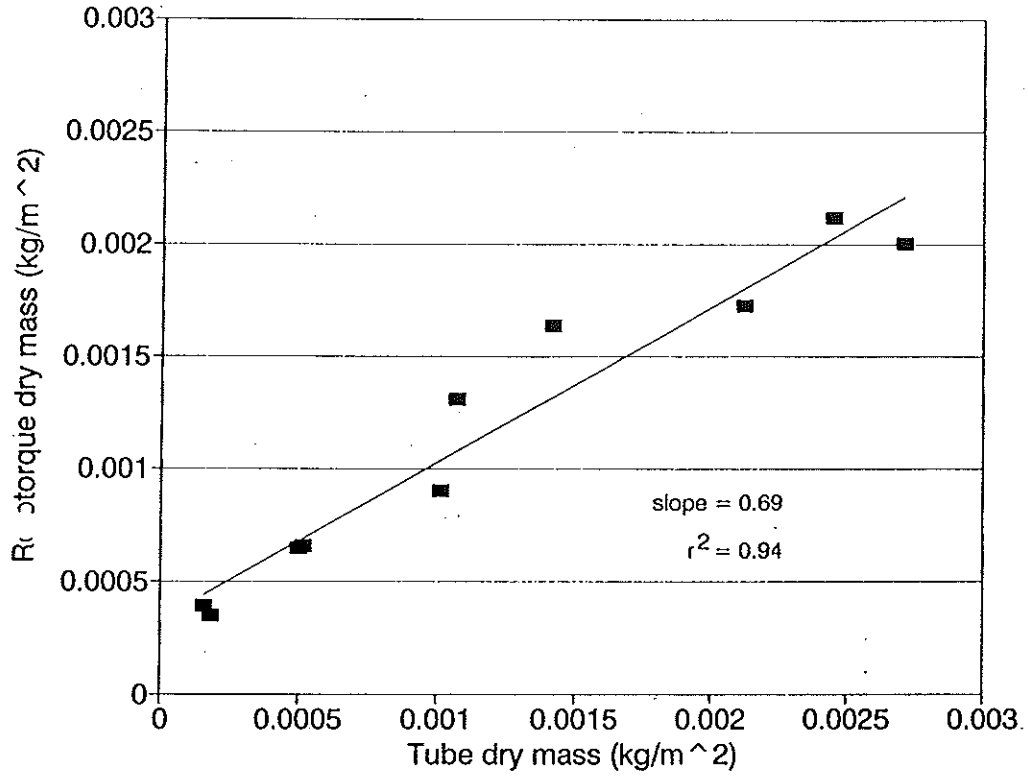


FIGURE 5. Annular reactor dry mass vs. tube dry mass.

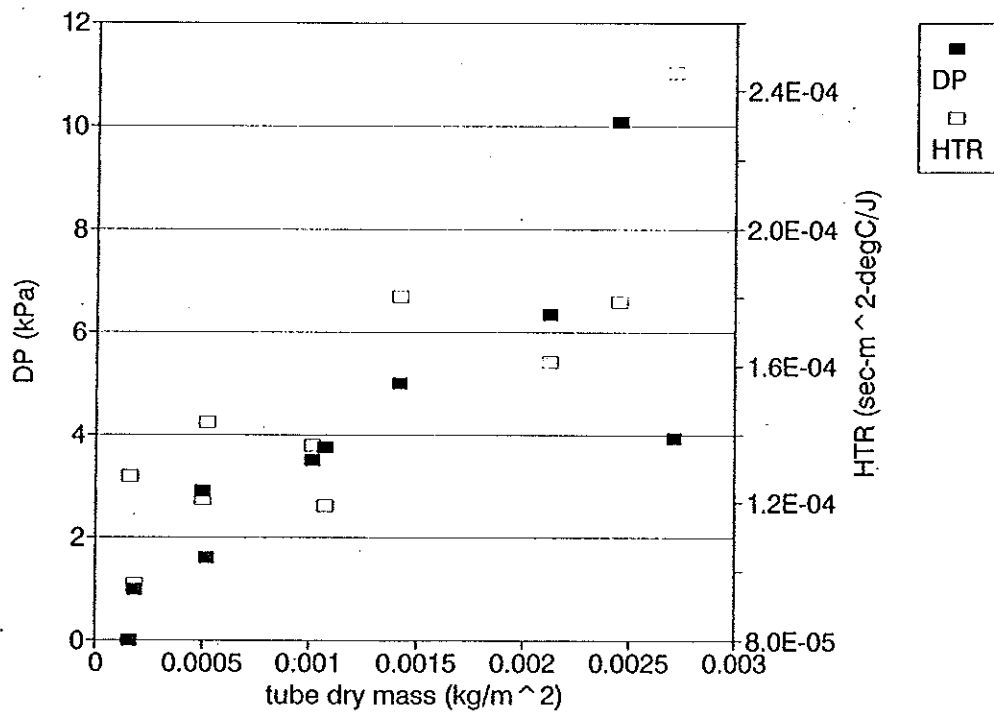


FIGURE 6. Differential pressure and heat transfer resistance vs. tube dry mass.

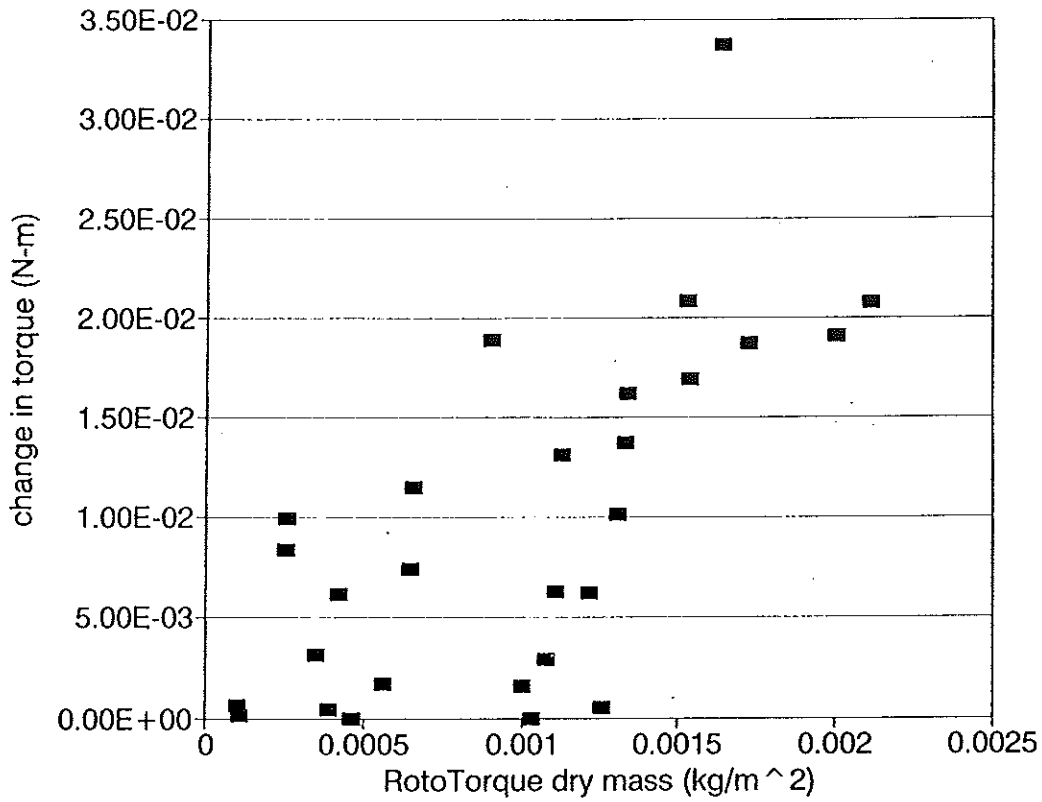


FIGURE 7. Torque vs. annular reactor dry mass.

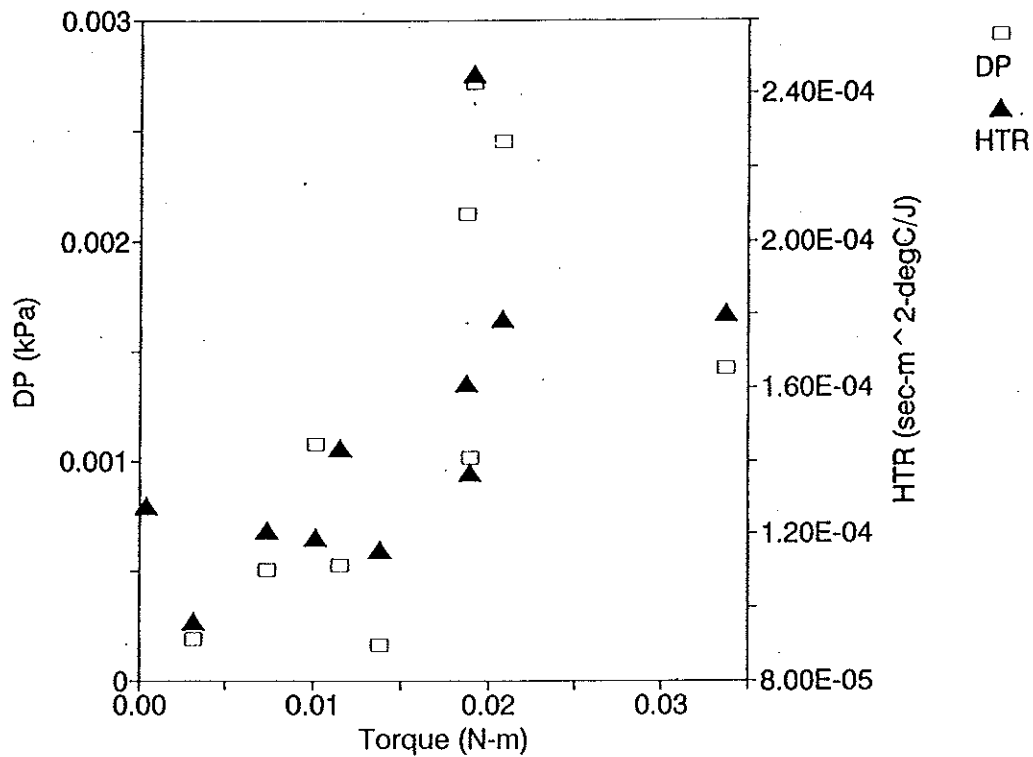


FIGURE 8. Differential pressure and heat transfer resistance vs. torque.

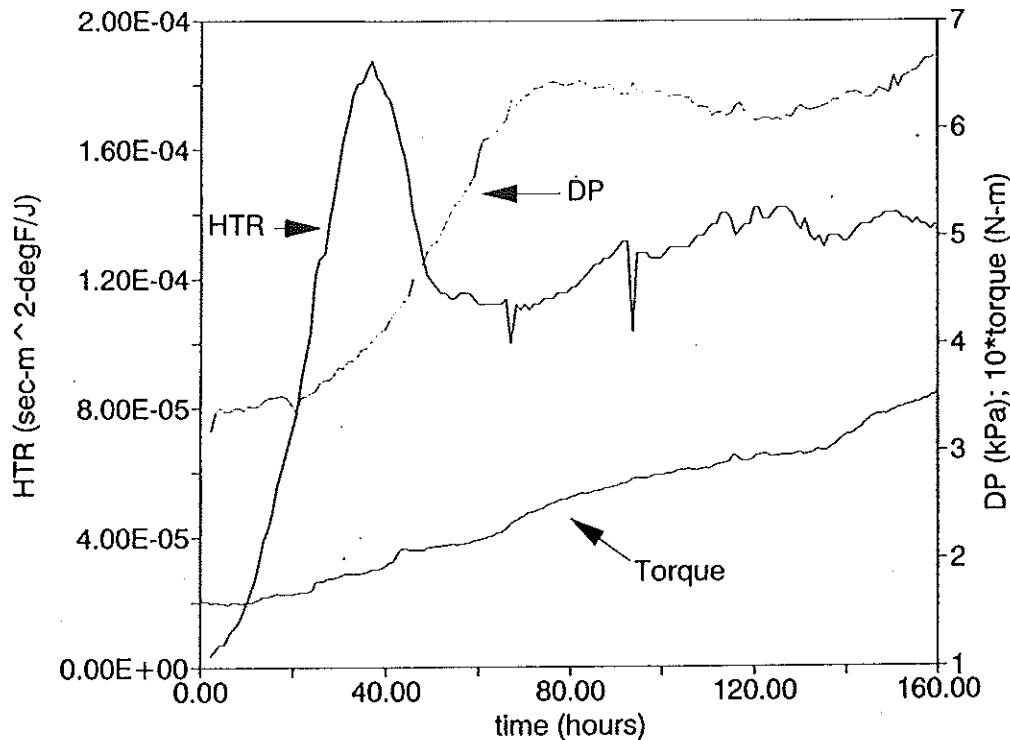


FIGURE 9. Typical experiment showing torque, heat transfer resistance, and differential pressure.

When two annular reactors were operated in parallel, their torque measurements tracked each other remarkably well (Figure 10). The computer-recorded data show very little noise.

Since the light-transmittance probe projected its beam against the rotating inner cylinder, it measured average biofilm density at the inner rotating cylinder wall. At the same time it also measured localized fouling at the outer wall, since it was mounted at a single point in that wall. Light-transmittance data points were a composite of these two measurements. Continually collected light-transmittance data, while showing little noise, did not correlate well with torque (Figure 11).

IV. DISCUSSION

Mass accumulation is a primary measure of fouling. It is important for developing models of fouling, and determining mass balances on fouling surfaces. The end-of-run areal mass comparisons in this investigation resulted in a slope of 0.69 (dry mass per unit area in the annular reactor/dry mass per unit area in the loop) with a correlation coefficient of 0.94. This relatively good correlation indicates that the annular reactors were successful at simulating biomass accumulation in the loop system and may be useful in predicting fouling in industrial tubular flow systems.

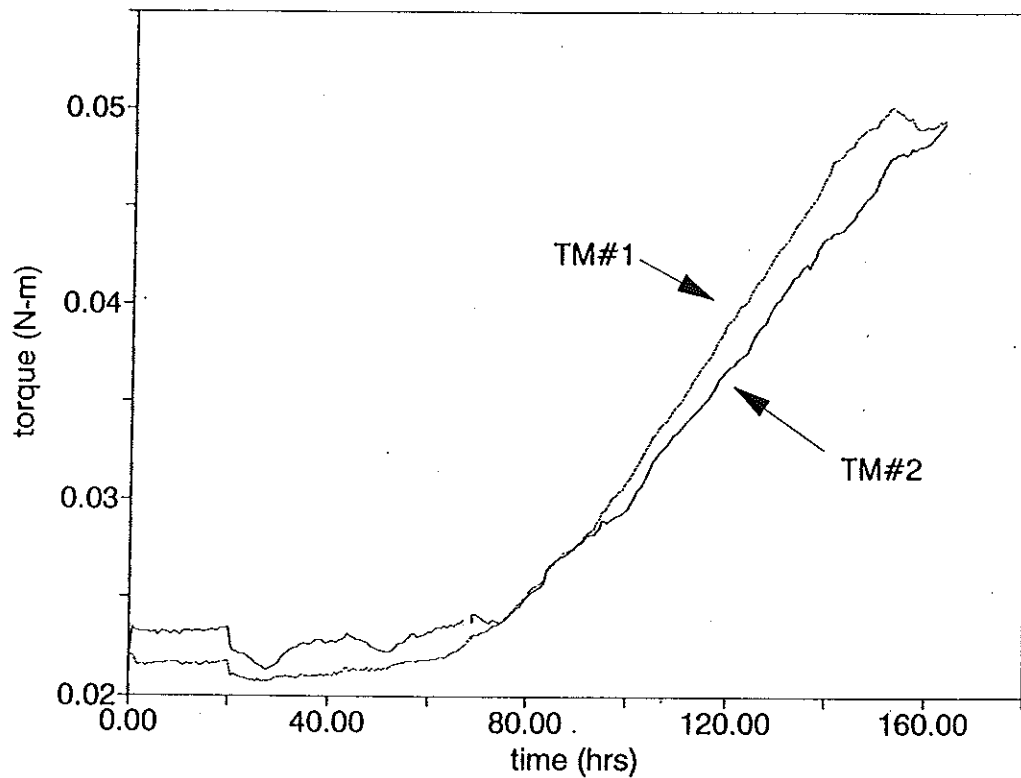


FIGURE 10. Two annular reactors operated in parallel.

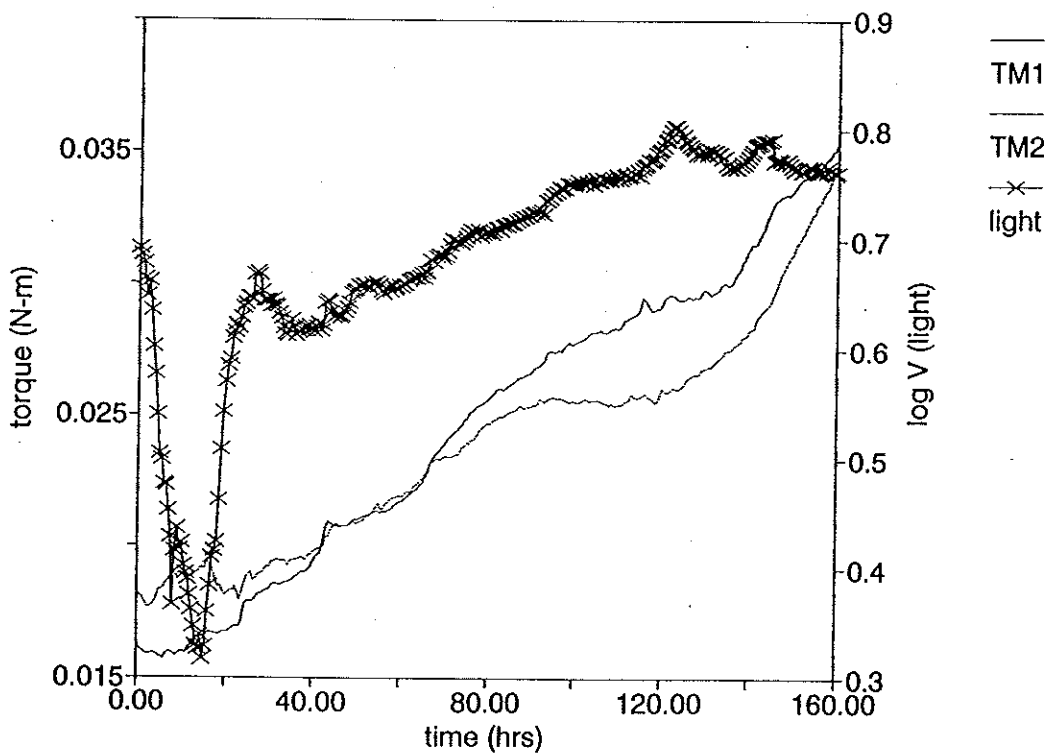


FIGURE 11. Torque and light transmittance during a run.

Ideally, a slope of 1.0 was expected, since chemical and hydrodynamic environments were matched. The low slope may have been a consequence of too high a flow rate in the loop system; a calculation error resulted in operating the loop at a flow rate 30% higher than intended. This high flow rate could have resulted in a thinner viscous sublayer and greater transport rates for nutrients and oxygen to the loop biofilm. The higher influx of nutrients and oxygen, and consequent higher growth rate, would have produced a higher mass accumulation in the loop system. Lewandowski and Walser⁹ observed that biofilm thickness increased with increasing shear stress to a maximum, and then decreased with further increase in shear stress. Their maximum occurred at a shear stress of about 0.45 N/m². Since this was considerably below the 2.7 N/m² shear stress calculated for our system, we should have observed higher rates of detachment due to shear rather than increased mass accumulation. The difference could be due to individual properties of different biofilms.

Unfortunately, the successful correlation seen above was limited to mirroring mass accumulation. Plots of end-of-run HTR, DP, and torque as functions of the relevant mass concentrations resulted in significantly poorer correlations. Biofouling effects (BEs), such as HTR, DP, and torque, are functions not only of mass accumulation, but of the biofilm hydrodynamic environments as well. Density, thickness, and roughness are all biofilm characteristics which strongly influence BEs. Since biofilms and their hydrodynamic environments may modify each other in unpredictable ways, these BEs may not show strong correlations to mass. Consequently, it was not surprising to find that increase in torque (1 BE) was not strongly correlated with either HTR or DP.

A second goal, that of finding a continuously measurable annular reactor BE which correlates well with loop system BEs, was not successful. Biofilm light transmittance measured in the annular reactor was not successful at predicting HTR or DP in the loop system.

This study made it clear that one must be careful when interpreting biofouling monitor data. The reactor may successfully mirror growth or accumulation of biofilms in a tubular system, while individual biofouling probes in the same reactor may fail in predicting BEs. In this case the annular reactor was successful in simulating accumulation of mass in a pipe system, while the biofouling probes failed to correlate with PD or HTR.

An encouraging finding — that two torque monitors closely track each other when annular reactors are run in parallel — suggests that torque can be used in comparative studies, e.g., testing biocides or control strategies.

Torque might also be used as an empirical trigger, warning of onset of biofouling.

V. CONCLUSIONS

The annular reactor was successful in simulating biofouling in a circular conduit or tubular system. This was demonstrated by good correlation between mass accumulation in the two systems.

Torque, while showing good sensitivity to biofouling and close tracking in duplicate monitors, exhibited somewhat poorer correlation with mass accumulation and with secondary fouling parameters such as HTR and DP.

Light transmittance through biofilm in the annular reactor was also a sensitive measure of biofouling, but, being a localized measurement, it demonstrated considerably more variability than the other biofouling probes.

Annular reactors exhibited a potential for practical application in industry. They may be operated in parallel for comparative testing of biocides or biofouling control strategies. They may also be used to simulate mass accumulation in a tubular system.

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