DEVELOPMENT AND IMPLEMENTATION OF A NEW MODEL TO MONITOR INDUSTRIAL PROCESS FOULING

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ABSTRACT

Fouling of a piping system refers to the formation of deposits on pipe walls which can severely impede fluid flow. The food, dairy and chemical processing industries usually combat the fouling of piping systems through extensive cleaning or complete replacement of the systems, usually on an emergency basis.

This paper describes the development of a model which permits real time monitoring of the overall fouling in a piping system and provides insight into the behavior and response trends of piping system fouling to changes in process operating parameters. It facilitates the prediction of both the rate of fouling and the useful life of the piping system, thereby avoiding emergency shut downs.

This paper also describes the implementation of the model in an existing industrial process plant where it was found to accurately monitor actual fouling behavior. The results of the model demonstrate the influence of Reynolds number upon the fouling of this industrial process piping system. This paper also presents a summary of previous fouling research.

INTRODUCTION

Fouling is the terminology often used to describe the accumulation of an unwanted substance at a material phase interface. In the context of piping systems and tubular heat exchangers, fouling refers to the formation of deposits on pipe or tube surfaces. Such deposits impede fluid flow and heat transfer.

Fouling is a complicated and dynamic process which is of considerable economic and technical importance. It severely affects the design, operation and maintenance of industrial piping systems and tubular heat exchangers. Hence, it increases the costs of nearly all industrial processes such as electric power production, crude oil refinement, and food, dairy and chemical processing. Pritchard (1981) estimates that the fouling of British heat transfer equipment results in an expense equal to about 0.5% of the British gross national product. Taborek et al. (1972a) claim that fouling is the major unresolved problem in heat transfer.

In addition to the degradation of heat transfer in tubular exchangers, fouling can also severely impact the hydrodynamic performance of piping systems. Picologlou et al. (1980) summarize case histories of fouling in water supply lines which show a flow capacity reduction as high as 55%. Such fouling of piping systems can be very costly. For example, the food, dairy and chemical processing industries utilize vast piping systems to transport process fluids within production plants. These industries usually combat the fouling of piping systems through extensive cleaning or complete replacement of the systems, many times on an emergency basis which results in a complete shut down of the industrial process. These emergency shut downs result in a loss of production and thus can be very expensive.

This paper describes the development and industrial implementation of a new empirical model which permits real time monitoring of the overall fouling in a piping system. This model incorporates parameters which are readily available from standard industrial instrumentation utilized in food, dairy and chemical processing plants. It provides insight into the behavior and response of piping system fouling to changes in process operating parameters. This model also facilitates the prediction of the useful life of the piping system. Such prediction can assist in the reduction of the frequency of emergency shut downs and thereby reduce the costs associated with fouling.

SUMMARY OF PREVIOUS RESEARCH

Due to its economic impact upon a wide variety of industries, fouling has been studied by a vast number of researchers, most of whom have been primarily concerned with the fouling of heat transfer surfaces rather than piping systems. This research is summarized in several historical review articles such as those written by Suitor et al. (1977), Epstein (1978, 1981) and Somerscales (1990). General discussions of the theory and mechanisms of fouling are given in the papers by Kern and Seaton (1959a, 1959b), Bott and Walker (1971), Taborek et al. (1972a), Pinheiro (1981), Epstein (1983) and Bott (1988a).

Taborek et al. (1972a), Epstein (1981, 1983), Knudsen (1984), Bott (1988a), Lira and Sengupta (1989) and others classify fouling into six primary categories:

1) Precipitation fouling (scaling): the formation of crystals from solution on the surface;
2) Particulate fouling: the accumulation of solid particles from the fluid stream on the surface;
3) Chemical reaction fouling: the formation of deposits on the surface by chemical reactions in which the surface material itself is not a reactant;
4) Corrosion fouling: the accumulation of indigenous corrosion products on the surface;
5) Biological fouling: the deposition and growth of micro-organisms and/or macro-organisms on the surface; and
6) Freezing fouling: the solidification of the process fluid or some of its constituents on the surface.

Hasson (1981) presents a detailed discussion of the mechanisms of precipitation fouling as well as a comprehensive review of previous scaling research and modeling efforts. Bott (1988b) addresses the fundamentals of crystallization and the mechanics of precipitation fouling. Using a constant flux heat exchanger, Hasson et al. (1968) measured calcium carbonate ($CaCO_3$) scale deposition while Hasson and Zahavi (1970) studied calcium sulfate ($CaSO_4$) precipitation fouling. Chan et al. (1988) proposed a silica scale deposition model that accounts for the effects of pH, salinity, supersaturation and thermal-hydraulic conditions. Reitzer (1964) analyzed the effects of scale properties, inverse solubility and crystallization velocity upon heat transfer.

A detailed review of particulate fouling is given by Epstein (1988b) in which he addresses the governing mechanisms, previous research and available models. Beal (1970) describes a method for predicting particulate deposition which includes the effects of inertia as well as Brownian and turbulent diffusion. Somerscales and Sanatger (1989) experimentally investigated re-entrainment of particulate deposits and proposed a mathematical model to predict this phenomena. Yung et al. (1989) experimentally studied the effects of turbulent bursts upon deposited particles within the viscous sublayer.

Fryer and Slater (1985) developed a numerical procedure to simulate chemical reaction fouling due to protein degradation in skimmed milk. Chemical reaction fouling in the petroleum industry has been studied by Braun and Hausler (1976), Perera and Rafique (1976), and Dugan et al. (1978).

Somerscales (1981) presents a detailed review of previous research on corrosion fouling. Somerscales and Kassemi (1987) conducted an experimental investigation of corrosion fouling in which they found that the degree of fouling on a 1010 carbon steel surface depends upon the transport of dissolved oxygen to the corrosion site.

Picologlou et al. (1980) studied the frictional losses in a piping system due to biological fouling. They represented these losses in terms of a dimensionless friction factor, derived from the Darcy-Weisbach equation, and an equivalent sand roughness, derived from the Colebrook-White equation. Pinheiro et al. (1988) related the thickness, weight and thermal resistance of biofilm fouling to fluid velocity, pH and surface characteristics. Lira and Sengupta (1989) experimentally investigated the influence of wall shear stress on biofilm fouling growth and removal.

A detailed discussion of freezing fouling is presented by Bott (1981) in which he reviews the governing mechanisms, previous research and available models. Bott and Gudmundsson (1974) analyzed freezing fouling due to the deposition of paraffin wax from kerosene flowing in cooled heat exchanger tubes.

For all six categories of fouling, Epstein (1983), Hasson (1981), Bott (1988b) and others have described the fouling process in terms of five stages:

1) Initiation: the nucleation or incubation of the fouling species at the surface or in the fluid stream;
2) Transport: the transport of the fouling species to the surface;
3) Attachment: the deposition of the fouling species on the surface;
4) Removal: the re-entrainment of the fouling species from the surface into the fluid stream; and,
5) Aging: the hardening or weakening of the fouling deposit with age.

Bott and Walker (1971), Taborek et al. (1972a), Epstein (1988a) and Bott (1988a) indicate that the combination of these five stages in various sequences leads to the four observed fouling behaviors shown in Figure 1:

1) Linear: fouling resistance monotonically increases at a nearly constant rate;
2) Falling Rate: fouling resistance monotonically increases at a decreasing rate;
3) Asymptotic: fouling resistance monotonically increases and approaches a steady state asymptote; and,
4) Sawtooth: fouling resistance exhibits a generally increasing trend punctuated with periodic decreases due to the shedding of fouling deposits.

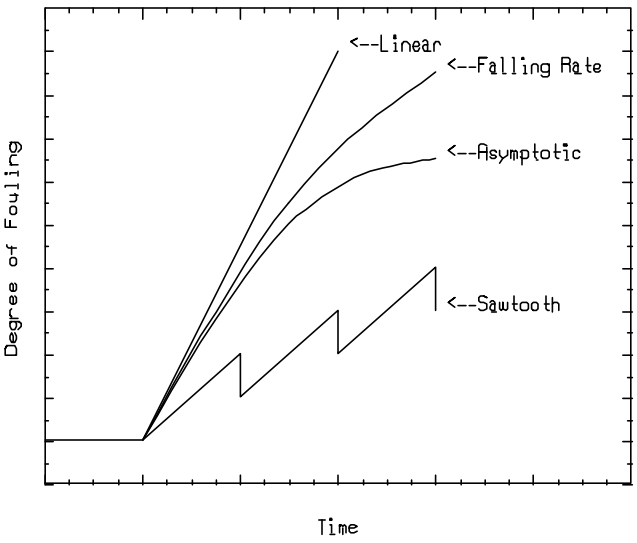

FIGURE 1. FOUR TYPES OF FOULING BEHAVIOR (AFTER EPSTEIN, 1988A)

Summary of Previous Fouling Models

It is generally accepted amongst researches that fouling behavior can be described by the Kern and Seaton (1959a) model:

$$\frac{d m_f}{d q} = \dot{m}_d - \dot{m}_r \qquad (1)$$

where $dm_f/d?$ is the net rate of change of the mass of the fouling deposit, $\dot{m}_d$ 2 is the fouling deposition rate and $\dot{m}_r$ 3 is the fouling removal rate. Kern and Seaton (1959a, 1959b) discussed the specific nature of the deposition rate, $\dot{m}_d$ 4, and the removal rate, $\dot{m}_r$ 5, for asymptotic particulate fouling. Since that time, the modeling efforts of researchers have focused upon developing expressions for $\dot{m}_d$ 6 and $\dot{m}_r$ 7 that realistically predict the behavior of the various categories of fouling (Hasson et al. (1968), Hasson and Zahavi (1970), Taborek et al. (1972b), Pinheiro (1981), Hasson (1981), Dunqi and Knudsen (1986), Epstein (1988a), Chan et al. (1988), Somerscales and Sanatgar (1989) and Somerscales (1990)).

For asymptotic fouling behavior, fouling resistance, R_f , can be expressed as follows:

$$R_f = R_f^* (1 - e^{-bq}) \qquad (2)$$

where R_f^* is the asymptotic fouling resistance, $?$ is time and $ß$ is a time constant. Equation (2) can be related to Equation (1) by expressing the asymptotic fouling resistance, R_f^*, and the time constant, $ß$, in terms of the deposition rate, $\dot{m}_d$ 9, and the removal rate, $\dot{m}_r$ 10.

Although these phenomenological models provide insight into the mechanisms of fouling, none of them provide a means for real time monitoring of industrial process fouling. Such real time monitoring would require some type of quantification or measurement of fouling.

Fouling Measurement Techniques

Epstein (1983) mentions three measures of fouling: 1) mass of deposit; 2) deposit thickness; and, 3) fouling thermal resistance. The first two measures require shut down and disassembly of the process line and hence would not be suitable for real time monitoring.

Fischer et al. (1975) describe how fouling thermal resistance can be determined from the degradation of the heat transfer coefficient. Local fouling measurement, used to determine fouling buildup at a single locality, is based upon the difference between the bulk fluid temperature and a temperature measurement from a thermocouple imbedded in the wall near the fouling surface. Overall fouling measurement, used to give an average value of fouling resistance over the total surface, is evaluated from the bulk fluid temperature at the inlet and outlet as well as the total heat transfer duty. Both

of these thermal fouling resistance techniques could be used to provide real time monitoring of the fouling in heat transfer equipment. However, they would be useless for industrial process fouling which does not involve heat transfer.

Dickakian (1989) states that crude oil fouling may be monitored on a daily basis by using an analysis derived from asphaltene/oil incompatibility. Obviously, such analysis would not be applicable to other types of fouling.

Picologlou et al. (1980) performed a series of experiments in which they measured the flow rate and pressure drop, ΔP, over a specified length, L, of pipe in a test rig. From this data, they calculated a dimensionless friction factor, f, by using the Darcy-Weisbach equation (Schlichting, 1979):

$$f = 2\frac{d}{L}\frac{\Delta P}{\rho V^2} \tag{3}$$

in which d is the clean pipe diameter, ρ is the fluid density and V is the average fluid velocity. They then related the friction factor, f, to an equivalent sand roughness, k_s, by utilizing a form of the Colebrook-White equation (Schlichting, 1979):

$$k_s = \frac{d}{2}\left(10^{(0.87\ -\ 0.50\ f^{-1/2})} - \frac{18.70}{f^{1/2}\ Re}\right) \tag{4}$$

in which Re is the pipe Reynolds number, $Re = Vd/\nu$, and ν is the kinematic viscosity of the fluid. They compared this equivalent sand roughness to an average fouling thickness determined by measuring the volume of the fouling material and dividing by the surface area of the test section. This "friction factor/equivalent sand roughness" technique could be adapted to provide real time monitoring of industrial process fouling.

Lira and Sengupta (1989) used a "friction factor/equivalent sand roughness" technique similar to that of Picologlou et al. (1980) to measure biofouling in a shell and tube heat exchanger. They compared these measurements to ones made using a thermal fouling resistance technique and found that the two sets of measurements did not always correlate. They attributed this discrepancy to the fact that in certain cases the fouling produced a greater surface roughness which enhanced the convective heat transfer in such a way that the heat transfer resistance appeared to be less. Thus, the "friction factor/equivalent sand roughness" technique may provide a more accurate method for real time monitoring of industrial process fouling.

DEVELOPMENT OF THE CURRENT MODEL

Motivation for the development of the current model arises from the transient nature of fouling in which the resistance to flow alternately increases and decreases in response to the competing processes of deposition and removal. The fouling of a piping system causes the flow passage to become constricted which can be visualized as a reduction in the "effective" diameter of the pipe. Thus, the fluctuation in fouling resistance is analogous to a fluctuation in the effective pipe diameter. The current model is based upon this concept of a fluctuating effective pipe diameter.

The measured input parameters required by the model are the pressure drop, ΔP, over a specified length, L, of the piping system and the average flow velocity, V. Assuming an initial estimate of the effective pipe diameter, D_i, the pipe Reynolds number, Re, is calculated:

$$Re = \frac{\rho V D_i}{\mu} \tag{5}$$

where ρ and μ are the fluid density and viscosity, respectively.

Churchill (1977) developed the following correlation which gives the Darcy friction factor, f, as a function of the pipe Reynolds number, Re, the pipe diameter, D, and the effective roughness, ε:

$$f = 8\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A\ +\ B)^{3/2}}\right]^{1/12} \tag{6a}$$

where

$$A = \left[2.457\ \ln\left(\frac{1}{\left(\frac{7}{Re}\right)^{0.9} + \frac{0.27\varepsilon}{D}}\right)\right]^{16} \tag{6b}$$

$$B = \left(\frac{37530}{Re}\right)^{16} \tag{6c}$$

Churchill states that this correlation is valid for all values of Re and ε/D.

In the current model, Equation (5) is used to calculate the pipe Reynolds number, Re, in terms of the estimated effective pipe diameter, D_i. This Reynolds number is then substituted into Equation (6) to yield the Darcy friction factor, f.

The Darcy-Weisbach equation (Schlichting, 1970) is then used to calculate an updated estimate of the effective pipe diameter, D_{i+1}:

$$D_{i+1} = \frac{f\ \rho\ V^2 L}{2\Delta P} \tag{7}$$

This new estimate of the effective pipe diameter is substituted into Equation (5) and the entire process repeated. Iteration continues until the difference between successive estimates of the effective pipe diameter satisfy the following criteria:

$$| D_{i+1} - D_i | < \chi \tag{8}$$

for a sufficiently small χ.

The converged value of the effective pipe diameter, D^*, is used to calculate the "degree of fouling," F, which is determined as the relative reduction in effective flow area, A:

$$\Phi = \frac{A^* - A_o}{A_o} = \frac{(D^*)^2 - D_o^2}{D_o^2} \qquad (9)$$

where D_o is the initial effective pipe diameter at the startup of operation of the piping system.

The degree of fouling, F, is a measure of the overall fouling of the piping system. The effective pipe diameter represents the resistance to flow due to fouling within the piping system and is not intended to represent the actual diameter of the fouled pipe at any particular location.

INDUSTRIAL IMPLEMENTATION OF THE MODEL

To demonstrate its utility, the current empirical model was implemented to monitor the fouling of a pH neutralization process line in an existing beverage production plant. This pH neutralization process line, shown schematically in Figure 2, has been in operation for over two decades and is typical of many industrial facilities with numerous flow restrictions and changes in flow direction. This process line occasionally fouls completely and almost always fouls to some degree within a week after a complete cleaning. The process line normally operates 24 hours per day, Monday through Friday, but not over the weekend. During the weekend shut down, the process line is cleaned and flushed with a caustic solution.

Description of the Industrial Process and Piping System

As shown in Figure 2, the process solution is pumped from the bottom of a 1000 gallon, 304 stainless steel supply tank by means of a five horsepower, 3480 rpm Tri-Clover centrifugal pump (model number C216MDG181-8) and enters the process line with an initial Reynolds number in the range of 8000 to 14000. Initially, this process liquor is 85% water and 15% dissolved organic solids by weight. It has an initial pH of approximately 10.0 and an initial temperature of about 180◦F.

After leaving the supply pump, the solution passes through a Micro-motion mass flow meter which also senses solution temperature. The Micro-motion mass flow meter monitors and maintains a constant mass flow rate of liquor by controlling a 316L stainless steel Fischer automatic flow control valve which is located just downstream of the Micro-motion meter. Following the Fischer flow control valve, there is a 316 stainless steel Anderson SP-series pressure transmitter which measures the upstream supply pressure. After the Anderson pressure transmitter, the flow of solution changes direction twice before encountering the acid injection. At this point, a 93% sulfuric acid solution with a pH of less than 1.0 is injected directly into the process line. During acid injection, a step function change in pH occurs in the vicinity of the injection point. However, the turbulent mixing within the process line quickly diffuses the concentrated sulfuric acid which reduces the pH of the liquor to a value between 5.5 and 6.0.

As shown in Figure 2, after acid injection, the process stream flows through nearly thirty feet of 1.5" and 2" schedule 40, 316L stainless steel pipe with seven changes in flow direction before

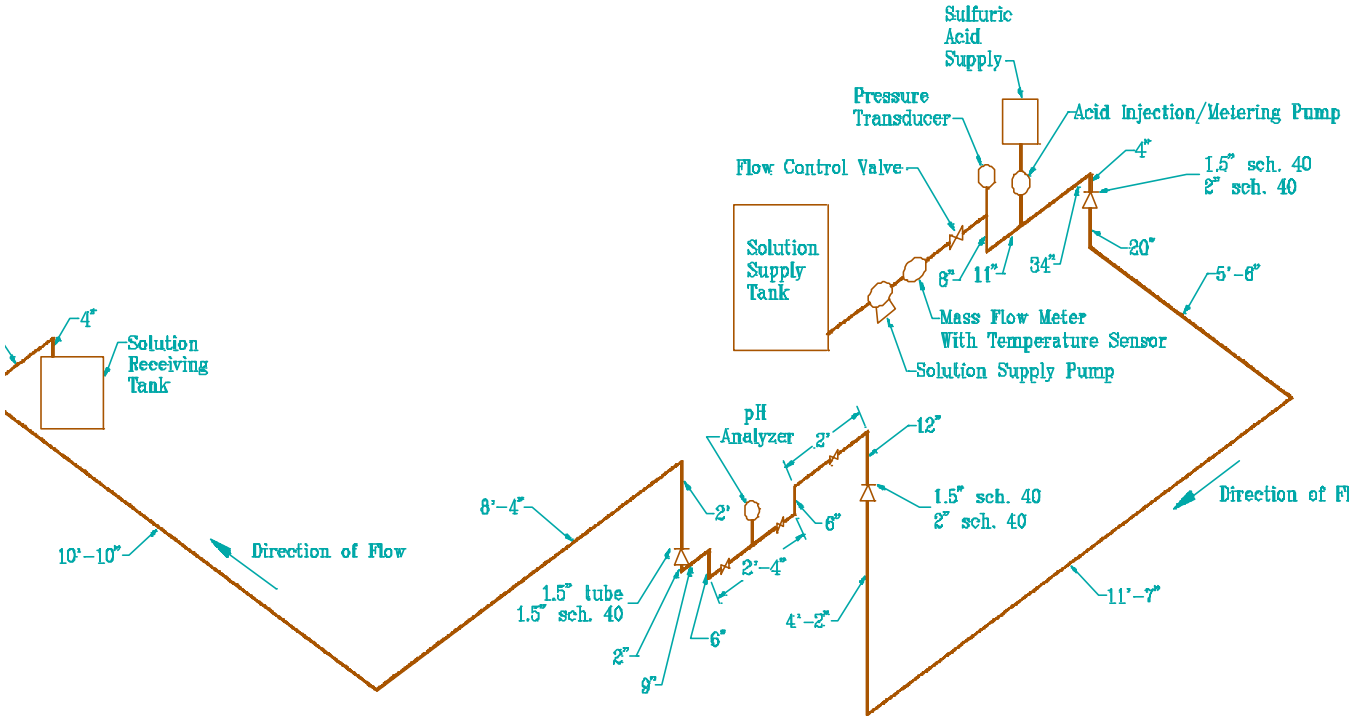

FIGURE 2. SCHEMATIC OF THE INDUSTRIAL PIPING SYSTEM

encountering the in-line, Leeds and Northrup single probe pH analyzer. Also, as shown in Figure 2, there are three manually operated, full port ball valves located in the vicinity of the Leeds and Northrup analyzer which are used for maintenance purposes.

The Leeds and Northrup pH analyzer monitors and maintains the pH of the solution by controlling the sulfuric acid injection/metering pump. To guard against fouling of the Leeds and Northrup analyzer, it is equipped with an automatic probe removal/hot water flush/probe return system which cleans the probe for one minute during every 30 minute interval. The acid injection/metering pump is a Branne and Lubbe diaphragm piston pump (model NP-41) which is constructed of Carpenter 20 Cb-3 stainless steel and delivers 0.0 to 11.8 gallons per hour at a maximum delivery pressure of 100 psig. The acid supply line is also made of Carpenter 20 Cb-3 stainless steel and the acid injection tee is lined with Kynar poly-vinylidene flouride polymer. After leaving the pH analyzer, the process stream flows through approximately 25 feet of 1.5" schedule 40, 316L stainless steel pipe and 1.5", 316L stainless steel tubing with seven changes in flow direction. It then discharges into a 1000 gallon, 304 stainless steel solution receiving tank at ambient pressure.

Description of the Instrumentation

As previously mentioned, in the industrial implementation of the current model, the process solution mass flow rate and temperature are monitored by a Micro-motion model RFT9712 mass flow meter with a 4-20 milliamp output. This instrument measures flow rate with ±0.2% accuracy and ±0.05% repeatability. It determines fluid density in the range of 0.0 to 5.0 gm/cm^3 with 0.001 gm/cm^3 accuracy and 0.0005 gm/cm^3 repeatability for fluids whose temperatures vary from -400°F to 842°F in ambient temperatures of -22°F to 131°F.

The Fischer flow control valve is a normally open, model 667EZ valve with a 3 to 15 psig control range, a 0.75 inch travel and a 1.0 inch port size. The Anderson SP-series pressure transmitter produces a 4 to 20 milliamp output and has a range of 0.0 to 100.0 psig with accuracy of ±0.5%, repeatability of ±0.1%, and hysteresis of ±0.1%, all with reference to full scale. It is rated for a temperature range of 20.0°F to 300.0°F.

The Leeds and Northrup pH analyzer is a model 7082, series pH/ORP single probe analyzer/controller with temperature compensation. It has a pH range of 0.0 to 14.0 with an accuracy of ±0.02 pH and a repeatability of ±0.014 pH. It produces a 4 to 20 milliamp output and is rated for a temperature range of -20°C to 60°C.

The output signals from these various instruments are transmitted via shielded cabling to a 30 channel, continuous feed Johnson/Yokogawa model 7082 chart recorder. Signals were recorded at two second intervals which monitored the following four process parameters: 1) Inlet temperature; 2) Inlet pressure; 3) Mass flow rate; and, 4) Final pH.

MODEL RESULTS

As mentioned in the previous section, four process parameters

(inlet temperature and pressure, mass flow rate and final pH) were recorded at two second intervals for approximately 600 hours over a four month period. Using the current model, this data was analyzed to gain insight into the behavior of the fouling which occurred in the industrial process line described above. The current model was utilized to calculate the time history of the degree of fouling, F, in the process line.

As discussed in the model development section of this paper, the degree of fouling, F, is determined as the relative reduction in the effective flow area and is a measure of the overall fouling of the piping system. It is calculated from the effective pipe diameter determined by the current model as a function of system pressure drop and mass flow rate.

Figures 3 through 7 are plots of the calculated degree of fouling, F, versus time for various weeks during the testing period. Each of these plots begins with a clean piping system at time equal to 0.0 hours corresponding to the beginning of the work week following a weekend shut down and cleaning. The effective pipe diameter calculated by the current model at this initial time is considered to be the baseline for the week.

Figure 3, corresponding to a Reynolds number of 8000 to 9000, shows nearly linear fouling behavior with very little initiation phase followed by a period of sawtooth behavior. At this low flow rate, the fouling deposition rate greatly exceeded the removal rate and the process line became completely fouled, requiring an emergency shut down and cleaning. The process line was then restarted at the same Reynolds number and displayed similar fouling behavior.

Linear fouling at a Reynolds number of 8000 to 9000 is also illustrated in Figure 4, however in this case, a six to eight hour initiation phase is evident. After this initiation phase, the degree of fouling rapidly increased until the process line became completely fouled. After cleaning, the process flow was restarted at a slightly higher Reynolds number but again displayed linear fouling behavior.

Figure 5 displays sawtooth fouling behavior at a Reynolds number of 9500 to 12,000. This behavior results from a higher competition between the deposition and removal processes.

Figure 6, at a Reynolds number of 10,000 to 12,000, shows a long initiation phase followed by asymptotic behavior. Such asymptotic behavior is achieved when deposition is nearly balanced by removal.

A stronger removal process is evident in Figure 7 at a Reynolds number of 10,000 to 14,000. At this high flow rate a large portion of the fouling deposits are periodically removed, resulting in the dramatic sawtooth behavior illustrated in this figure.

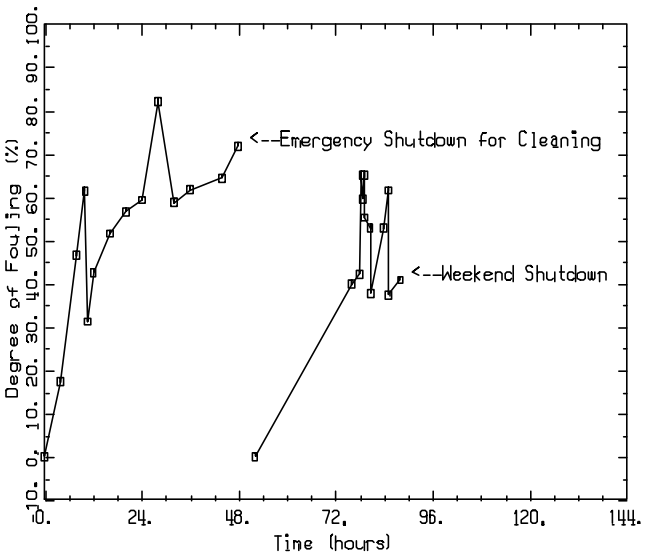

FIGURE 3. TIME HISTORY OF FOULING FOR A REYNOLDS NUMBER IN THE RANGE OF 8000 - 9000

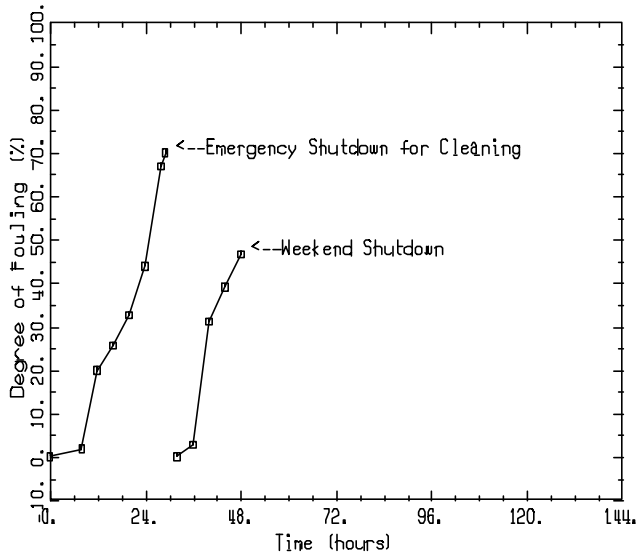

FIGURE 4. TIME HISTORY OF FOULING FOR A REYNOLDS NUMBER IN THE RANGE OF 8000 - 9000

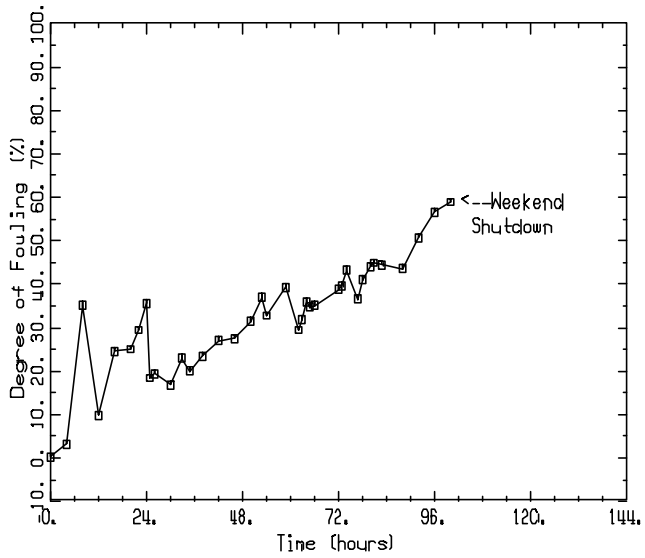

FIGURE 5. TIME HISTORY OF FOULING FOR A REYNOLDS NUMBER IN THE RANGE OF 9500 - 12000

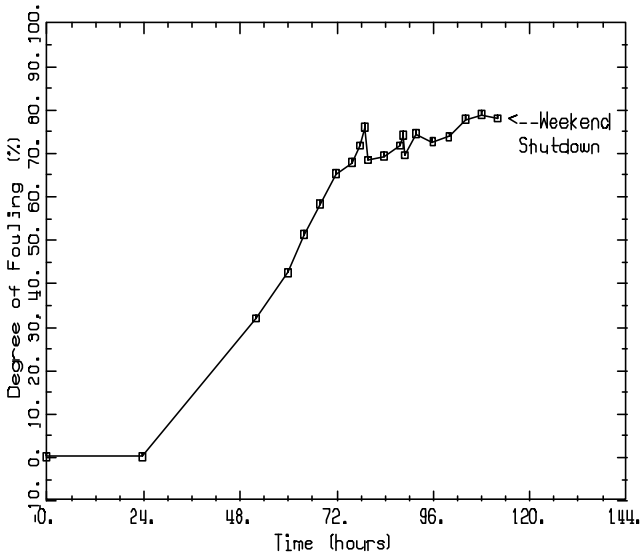

FIGURE 6. TIME HISTORY OF FOULING FOR A REYNOLDS NUMBER IN THE RANGE OF 10000 - 12000

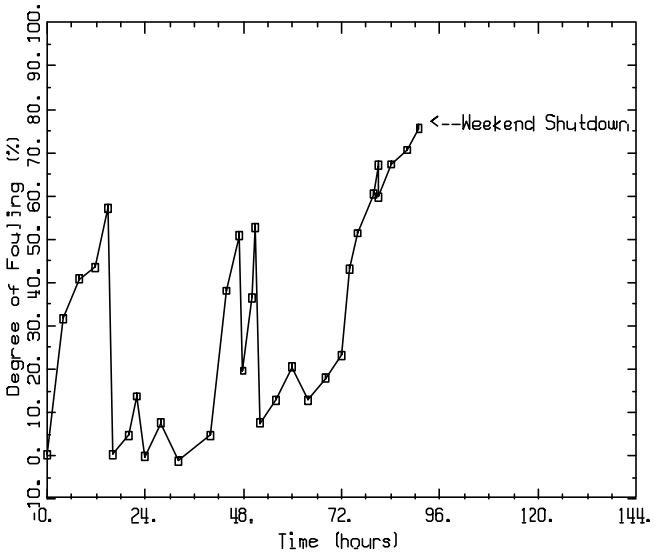

FIGURE 7. TIME HISTORY OF FOULING FOR A REYNOLDS NUMBER IN THE RANGE OF 10000 - 14000

FOULING ANALYSIS

It is evident from the model results that the Reynolds number dramatically influences the fouling behavior in this industrial process. It appears that a Reynolds number of 10,000 is critical to this industrial process fouling. When the Reynolds number is less than this critical value, the deposition rate is much greater than the removal rate which leads to a complete fouling of the system. At Reynolds numbers exceeding 10,000, the removal rate more nearly balances the deposition rate, thus avoiding emergency shut downs and extending the period of operation.

As discussed in the description of the industrial process and piping system, the process liquor initially has a pH of 10. Near the beginning of the process line, a 93% sulfuric acid solution is injected directly into the line with the hope that turbulent mixing will quickly bring the final pH of the solution to a value between 5.5 and 6.0. However, during acid injection, a step change in pH occurs in the vicinity of the injection point which could lower the instantaneous, localized pH to values approaching 1.0. Laboratory analysis of the process liquor shows that a precipitate is generated at a pH of approximately 3.0 or less. Therefore, precipitation fouling could occur if the turbulent mixing in the process line is not sufficiently intense to rapidly diffuse the concentrated sulfuric acid.

This precipitation fouling hypothesis substantiates the Reynolds number dependence of the industrial process fouling. At higher Reynolds numbers, the mixing within the process line would be more intense, reducing the period during which the localized pH is below 3.0 and thus minimizing the precipitation deposition rate.

The process line was disassembled and visually inspected. Visual inspection of a cross section of the fouled process line, shown in Figure 8, reveals that deposition occurred nearly uniformly around the circumference of the pipe, typical of precipitation fouling. The thickest deposits were found slightly downstream from the acid injection point. Deposit thickness then decreased with distance downstream from that point. Minimal deposits were found upstream from the acid injection point.

In summary, all of this evidence indicates that this industrial process fouling is an example of Reynolds number dependent, precipitation fouling.

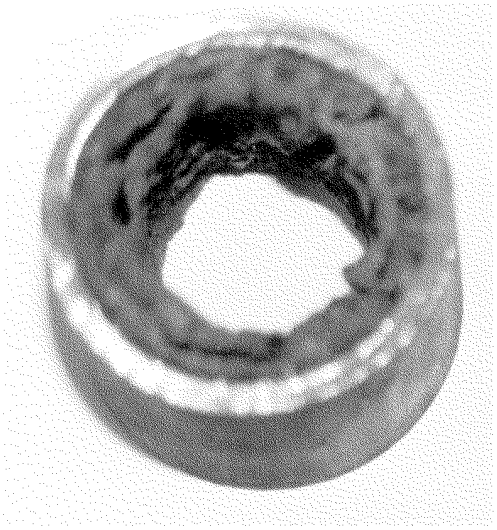

FIGURE 8. CROSS SECTION OF FOULED PROCESS LINE

CONCLUSIONS

This paper has focused upon the development of a model which permits real time monitoring of the overall fouling in a piping system. The model was implemented in an existing industrial process plant where it was found to accurately monitor actual fouling behavior. The results of the model demonstrate the influence of Reynolds number upon the fouling of this industrial process piping system. Further analysis of the fouling of this industrial process substantiates its Reynolds number dependence.

Furthermore, it is evident that this type of information, gained through real time monitoring of the fouling of the piping system, would facilitate the avoidance of emergency shut downs during operation of the industrial process. It would provide insight into the behavior and response trends of the piping system fouling to changes in process operating parameters, thus extending the useful life of the piping system.

This paper has also presented a summary of previous fouling research, modeling efforts and measurement techniques.

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