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CHAPTER 48

Control of Microbial Fouling in Circular Tubes with Chlorine

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Microbial fouling is a major cause of energy loss in water pipelines, heat exchangers, and power-plant condensers. Chemical control is usually by chlorine addition. New restrictions on effluent chlorine residuals require that chlorine be added judiciously. The work described is the basis for a methodology to determine optimum chlorine dosing rates for fouling control. Tubular reactor experiments were conducted for turbulent conditions (Reynolds number 13,000-19,000). Microbial film thickness (T) was monitored by electrical conductivity (±2.5 μm) and correlated well with increases in frictional resistance measured by pressure drop (Δp). Observed Δp was significantly higher than predicted based on reduction of cross-sectional area available for flow, and Δ p increases of 200% were observed for T>100 μm. Chlorine addition caused partial film removal with consequent increases in effluent particulates. A mathematical description of microbial film growth and its control by chlorine is offered.

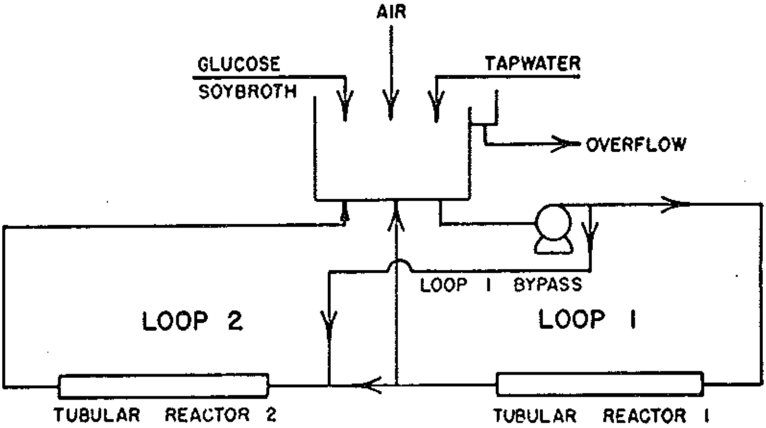
INTRODUCTION

Microbial fouling is a major cause of energy losses in water pipelines and heat exchangers. Thin microbial films attach to the inside of water conduits causing large increases in both fluid frictional and heat transfer resistance. Characklis (1973a,b) and Norrman (1976) reviewed the literature concerning the effects of fouling on frictional resistance. Chlorine generally is used for controlling microbial fouling in such systems. However, both economic considerations and increasingly stringent environmental regulations require a systematic understanding of microbial fouling, its effects, and methods of control. This paper describes research directed toward the following objectives:

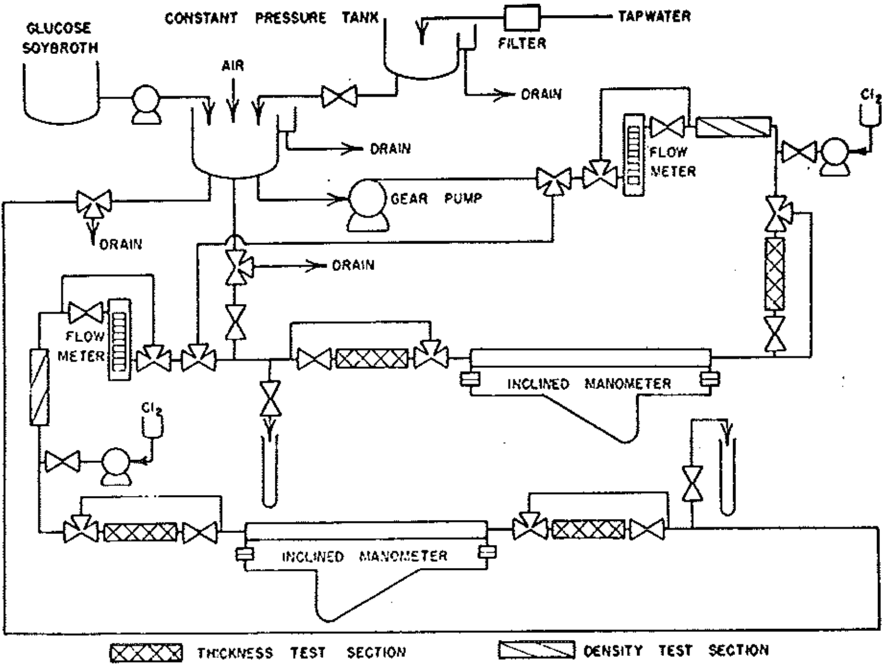
1. Development of a suitable apparatus for experimental determination of frictional resistance as a function of film thickness.
2. Determination of the dependence of frictional resistance on film thickness and flow rate.
3. Determination of the effect of varying chlorine application rates on film thickness and frictional resistance.
4. Development of mathematical models describing both film growth and film destruction by chlorine.

MATERIALS AND METHODS

System description. A tubular reactor was used for reasons of dynamic similarity to full-scale systems. Figure 1 is a schematic diagram of the experimental apparatus. Two loops permitted simultaneous experiments at different flow rates. Each loop contained a rotameter and separate sections for film thickness, film density, and pressure drop measurements. The entire system, including test sections (Fig. 2), was acrylic tubing (1.27 cm I.D.) roughened to promote microbial attachment. The tubular reactors were operated on a once-through basis during chlorine addition.



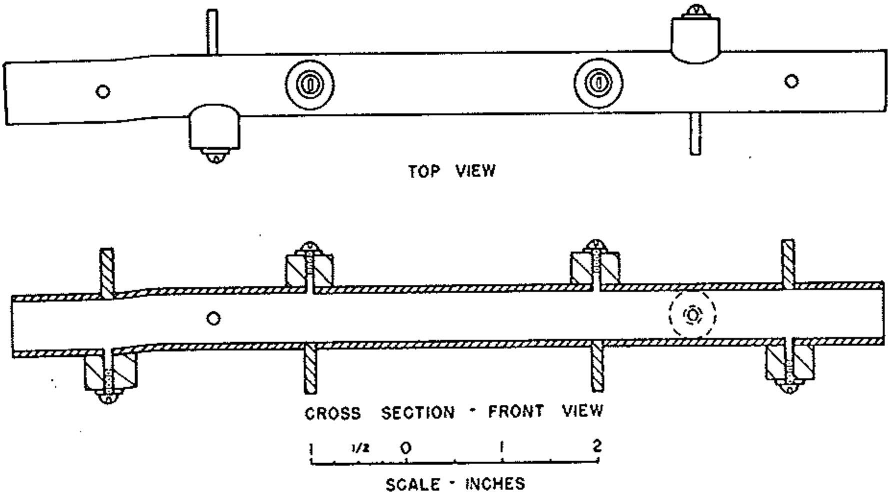
G. 1. Schematic diagram of the experimental system.



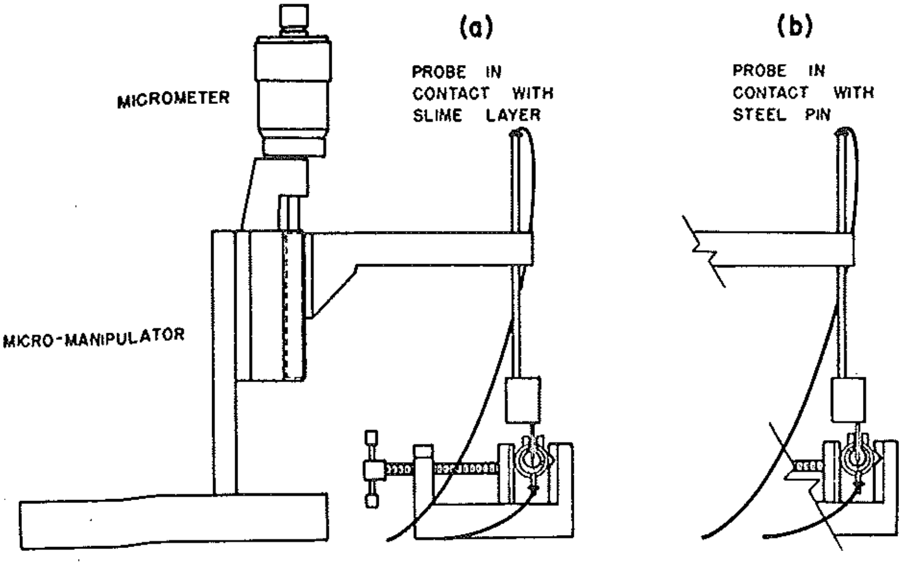
G. 2. Detailed diagram of experimental system.

nalytical. Free and total chlorine concn were determined by colorimetric analysis (LaMot hemical Products Co.). All glassware was saturated with chlorine prior to analysis. Suspende lids were measured by filtering 100 ml samples through pre-dried Nucleopore filters (average ore size = 0.4 μm). Flow rates were established using Dwyer rotameters (2-13 l/min). An clined mercury manometer was used to record all pressure differentials over a 500-cm length ction.

ensity of microbial films was determined from film dry weight in a section of tubing with n surface area and a measured film thickness. Thickness of attached biofilms was mined using a method adapted from Hoehn (1970). Test sections consisted of acrylic g with a 3-mm stainless steel rod imbedded normal to the tube, flush with the inner wall 3). Opposite each rod was a hole sealed during experimentation with a set screw. The section was removed from the system and clamped to the base of a micro manipulator e (Fig. 4). The set screw was removed, and a needle coupled to a micrometer was ted. Both needle and steel rod were connected to a voltage source and an electrometer,



. 3. Detail of test section for measuring film thickness.



G. 4. Film thickness measurement apparatus.

ning an open circuit. A current registered on the electrometer and a depth reading was en when the needle contacted the film surface. A second deflection and depth were noted en the needle contacted the steel rod. Film thickness was the difference in the two rometer readings. Measurement precision was ±6.0%. Thickness determinations of thin tal strips with a Vernier micrometer and the above method were used to establish the uracy of the measurement. Measurements by both methods were not significantly different 95% confidence level (Aspin-Welch test).

perimental procedure. Experiments were initiated as batch runs to reduce the induction iod for microbial attachment. The reactor was charged with a solution of 500 mg/ℓ cose, 500 mg/ℓ soy broth, and 10% v/v filtered (Whatman #5 filter) primary treated vage. Recirculating flow rates were adjusted in reactor loops 1 and 2 to 11.4 1/min and 7.6 nin, respectively. Continuous feed was started in 1-3 days. System detention time was intained at 12-15 min. Glucose feed concn was 10 mg/ℓ and soy broth was 10 mg/ℓ.

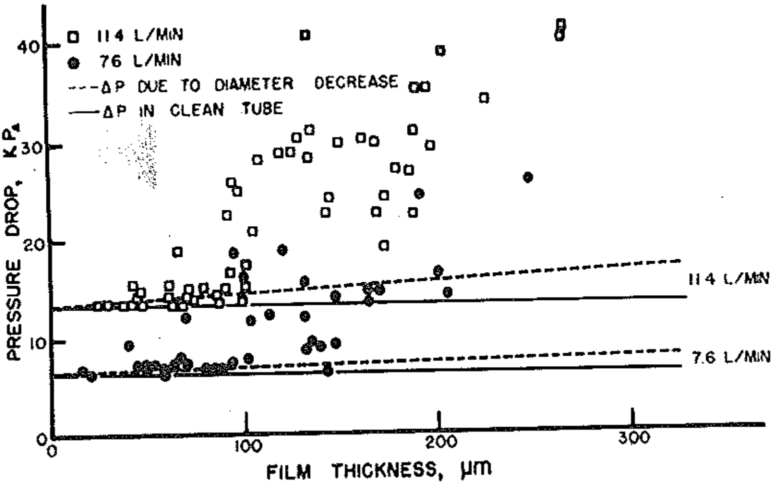
A two-level (2^2) factorial experiment was conducted to determine effects of chlorination on attached film growth and related frictional resistance. One variable was the amount lorine added to the system: 2.0 g/day or 4.1 g/day. Two rates of chlorine application we vestigated: shock or continuous chlorination.

Shock chlorination consisted of injecting chlorine into the system over a 30-min period ch day or every other day. Continuous chlorination experiments lasted for 48 h. Because y broth exerts a significant chlorine demand and also because film organisms would be fected if deprived of soy broth, alternating hourly applications of chlorine followed by the y broth-glucose mixture simulated continuous chlorination. In either chlorination techque, recycle operation was ceased, and the system operated as a once-through reactor. ressure drop, glucose concn, film density, film thickness, and suspended solids were eriodically recorded during the film growth phases of experiments. Prior to chlorination, ressure drop and film thickness were recorded and suspended solids samples removed. During ontinuous chlorination, pressure drop was recorded hourly, while samples for suspended olids and chlorine concn were taken every 6 h. Similar measurements were performed every 5 nin during shock chlorination except for film thickness.

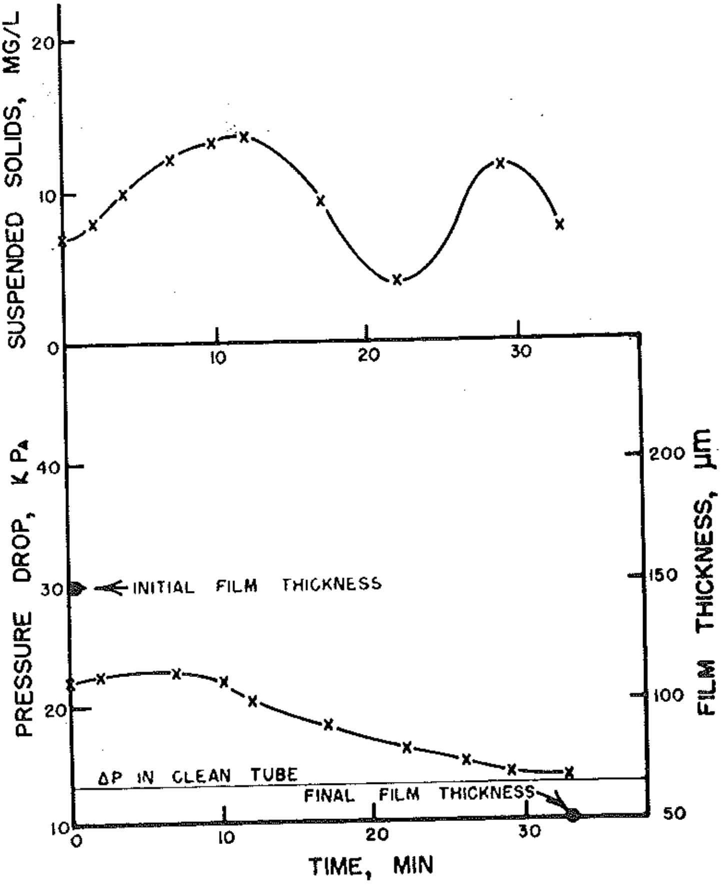
RESULTS AND DISCUSSION

ilm Growth and Frictional Resistance

igure 5 presents the relationship between pressure drop and film thickness at two flow rates. espite the scatter, an S-shaped curve represents the data well. Further rationale for such a unction is provided by data of Kornegay (1969) and Characklis (1970). Results indicate that rictional effects of relatively thin films (less than 100 μm) are no larger than expected for the esulting decrease in cross-sectional area available for flow. However, at some critical hickness, frictional resistance increases sharply with thickness. Microbial films are viscolas in nature and frequently exhibit rippled surfaces which are the cause for relatively h pressure drops compared to rigid surfaces of the same configuration (Schuster 1971). These results suggest that the film surface is relatively smooth until it reaches the critical thickness, signifying onset of growth and hydrodynamic processes which cause a rippling of the film surface. As an example, friction factors characteristic of an equivalent sand roughness equal to 420 μm were common, although film thickness rarely exceeded 200 μm.



G. 5. Effect of film thickness on pressure drop in a 1.27-cm circular tube.

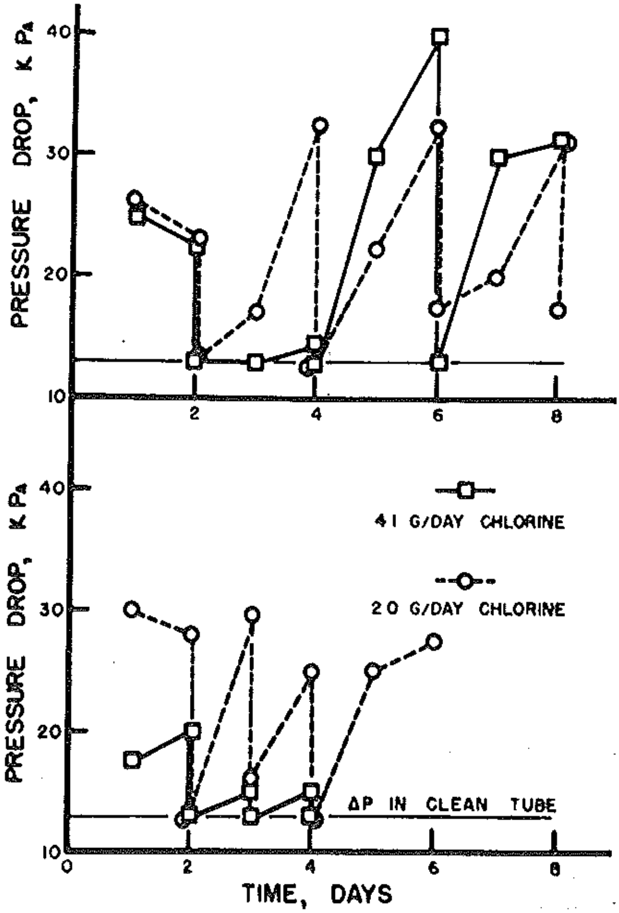


IG. 6. Pressure drop, thickness, and suspended solids concn during shock chlorination at 4.1 mg/ℓ and flow rate = 11.4 l/min.

rination

ous work (Characklis and Dydek 1976) indicated that chlorine reacts with extracellular saccharides which provide structure for slime films. Bactericidal effectiveness of chlorine atively insignificant in controlling established microbial films. Consequently, monitoring sure drop and film thickness was extremely important for determining the effect of rine. Results of a shock chlorination experiment are presented in Fig. 6. Film thickness eased from 165 μm to 50 μm, with a concurrent decrease in pressure drop. Pressure drop inued to decrease after termination of the chlorine feed in some cases. The "residual" ct could be due to deterioration of the slime matrix by chlorine oxidation followed by ion of the film by shear forces. Chlorine concn remained relatively constant throughout treatment period although prolonged addition would certainly cause an increase equent to complete slime removal. Resulting increases in suspended solids concn due to rination verify the disrupting effect of chlorine on the microbial film (suspended solids cn prior to chlorination was zero).

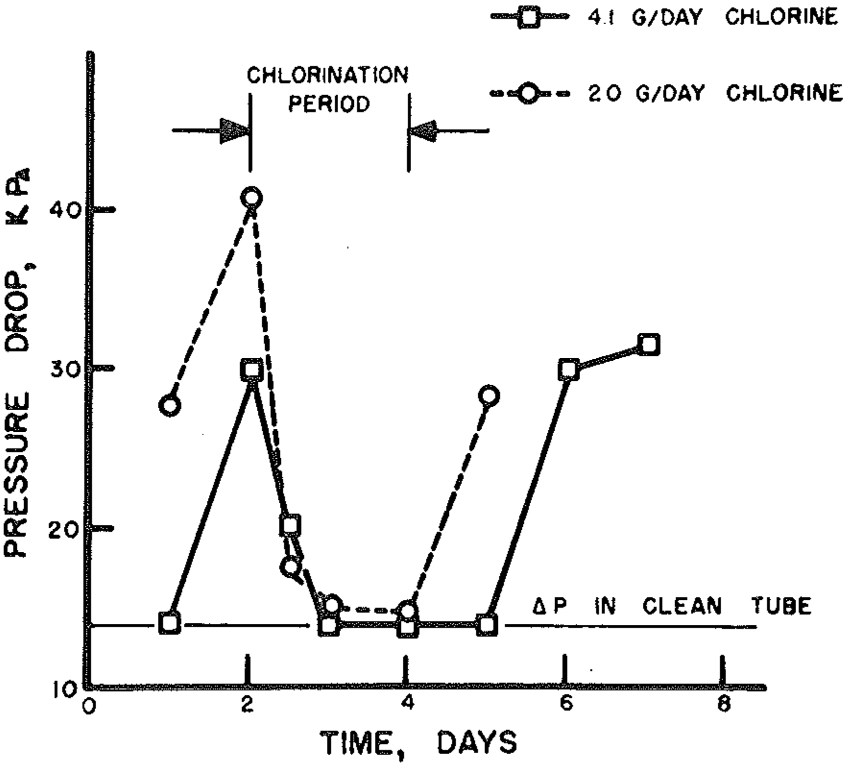
igure 7 compares results from varying shock chlorine dosages and application rates. Data cate relatively rapid recovery of slime film following chlorination every other (



IG. 7. Shock chlorination effect on frictional resistance.

;ardless of the chlorine dosage. Indications are that 4.1 g/day chlorine added every other y is sufficient for controlling frictional resistance. Dosing at 2.0 g/day results in rapid :overy comparable to growth observed when dosing every other day.

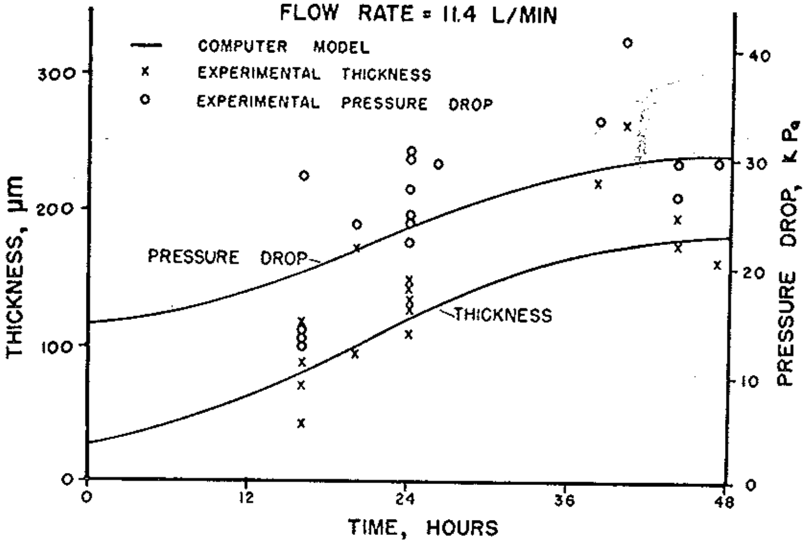
One day of continuous chlorination results in full recovery of tube flow capacity at either sing level. After chlorination was stopped, however, films treated at 2.0 g/day increased ıch more rapidly than those treated at 4.1 g/day chlorine (Fig. 8). Measurable film ıcknesses were observed in all cases following chlorination but were decreased below critical el when dosed at high levels. In such cases, an increase in pressure drop occurred only when n thickness increased beyond the critical level.



;. 8. Effect of continuous chlorination on frictional resistance at flow rate = 11.4 l/min.

athematical Description

'lm growth. Transient growth of attached film was simulated by three coupled, nonlinear fferential equations describing material balances on substrate, suspended biomass, and film ıckness. Microbial growth and substrate utilization kinetics were described using Monod rate pressions similar to those of Kornegay (1969). Accumulation of attached film was nsidered the net difference between (1) attachment and growth rates, and (2) shear pendent removal rates. Conventional hydrodynamic relationships were used for wall shear ess and pressure drop calculations, with experimental data providing the dependence of ctional resistance on film thickness. Equations were solved simultaneously using the IBM ›ntinuous System Modeling Package, CSMP. Comparison of computer fit and experimental sults are presented in Fig. 9.



. 9. Comparison of computer model and experimental data for thickness and pressure drop development.

lorine utilization. Figure 10 shows chlorine utilization rates, R_C, versus chlorine concn for ck applications. Utilization rate was defined as

$$R_C \quad = \quad \frac{(C_i - C_e)\ Q}{2\pi\ (r - T)\ L} \tag{1}$$

where

C_i = feed chlorine concn, mg/liter
C_e = chlorine concn in effluent, mg/liter
Q = volumetric flow rate, liters/min
r = tube radius, cm
T = film thickness, cm
L = test section length, cm

imple rate expression of the following form was proposed:

$$R_C \quad = \quad k \cdot (C_i)^n \tag{2}$$

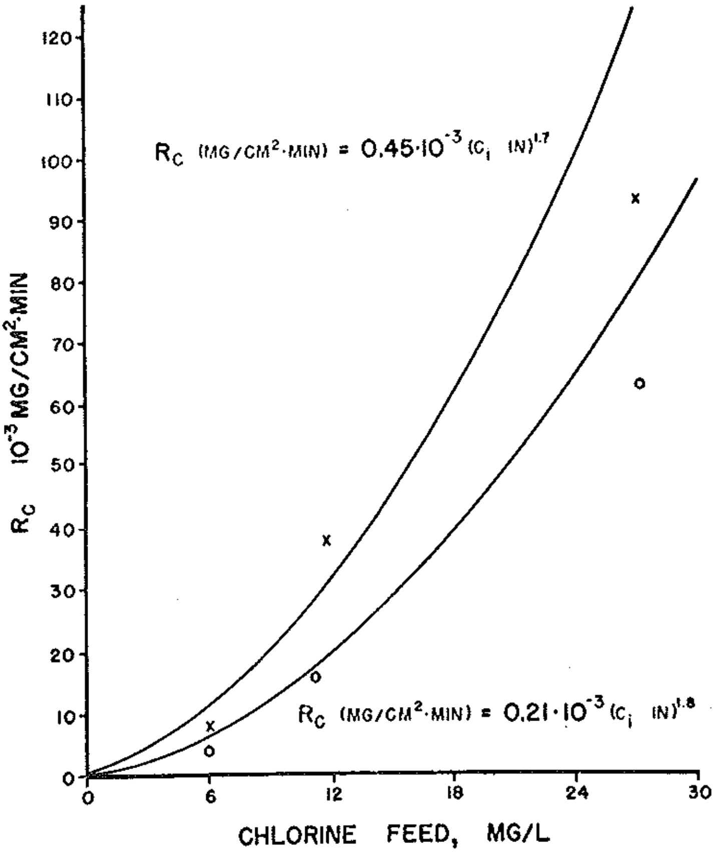
ch resulted in the following constants using linear regression analysis:

$$R_C \quad = \quad (0.45 \times 10^{-3}) C_i^{1.7} \qquad \text{for } Q = 11.4 \text{ l/min} \tag{3}$$

$$R_C \quad = \quad (0.21 \times 10^{-3}) C_i^{1.8} \qquad \text{for } Q = \ \ 7.6 \text{ l/min} \tag{4}$$

relation coefficients for equations 3 and 4 were 0.96 and 0.95, respectively.

Higher chlorine utilization rate at higher flow rates can result from higher shear forces



G. 10. Chlorine utilization rate as a function of chlorine feed for shock additions.

srupting the film and exposing new reaction sites, thus providing a larger surface area for the lorine reaction. Higher flow rates also result in larger eddy diffusivities, suggesting another ason for higher apparent reaction rates. Regardless, increased flow rates during chlorination proves chlorination efficiency.

The rate equation for film removal during chlorination was hypothesized as follows:

$$R_T = k' \cdot (T_o)^n \cdot (C_i)^o \cdot (Q)^P \tag{5}$$

where

R_T = $-dT/dt$, cm/min
T_o = film thickness prior to chlorination, cm
C_e = feed chlorine concn, mg/liter
Q = volumetric flow rate, liters/min

near regression based on the logarithmic form of equation 5 resulted in the following uation:

$$R_T = (-0.084) T_o^{1.34} \tag{6}$$

ich indicates film deterioration following chlorination depends only on initial film ckness (between 45-265 μm) and not on flow rate. Presumably, chlorine disrupts film ıcture and shear forces actually remove portions of attached film weakened by the ·mical oxidation.

CONCLUSIONS

Frictional resistance caused by attached film cannot be modeled by assuming a smooth, rigid surface but requires consideration of flow past a rippled, compliant, viscoelastic boundary. This is only true after film growth exceeds a critical thickness characteristic of the fluid shear rate.

Flow rate (7.6-11.4 l/min) does not significantly affect film attachment or growth.

Chlorine utilization rate is a function of chlorine feed concn according to the expression:

$$R_C = kC_i^n$$

Film removal rate due to chlorination is dependent upon film thickness prior tc chlorination according to the expression:

$$R_T = k'T_o^m$$

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