

MICROBIAL FILMS AND ENERGY LOSSES

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## ABSTRACT

Fouling microbial film formation can cause significant energy losses as reflected by increased fluid frictional resistance and heat transfer resistance. Methods to predict and monitor rate of microbial film formation and its effect on energy losses in different environments is essential for efficient design and operation of engineering systems. This paper will discuss measurement methods and their incorporation in predictive mathematical models.

NOMENCLATURE

A = wetted surface area	$(L^2)$
$C_p$ = specific heat	$(L^2 t^{-2} T^{-1})$
f = friction factor, $2\Delta p / L \rho_f v_m^2$	(dimensionless)
h = convective heat transfer coefficient at $r_I$	$(Mt^{-3} T^{-1})$
k = fluid thermal conductivity	$(MLt^{-3} T^{-1})$
$k_A$ = adsorption rate coefficient	$(Lt^{-1})$
$k'_A$ = saturation coefficient	$(ML^{-2})$
$k_B$ = apparent thermal conductivity of biofilm	$(MLt^{-3} T^{-1})$
$k_A$ = detachment rate coefficient	$(t^{-1})$
$k'_D$ = coefficient	$(Lt^2 M^{-1})$
$k_p$ = specific biofilm production rate	$(t^{-1})$
$k'_p$ = saturation coefficient	$(ML^{-3})$
$k_t$ = thermal conductivity of tube wall material	$(MLt^{-3} T^{-1})$
L = length of heat exchanger tube	(L)
N = rate of nutrient consumption by biofilm	$(ML^{-2} t^{-1})$
Pr = Prandtl Number	(dimensionless)
r = radial distance	(L)
$r_1$ = inner radius of tube	(L)
$r_2$ = outside radius of tube	(L)
$r_i$ = radial distance to inner thermistor of TWHE	(L)
$r_{ii}$ = radial distance to outer thermistor of TWHE	(L)
$r_I$ = radial distance to the biofilm	(L)
$R_A$ = net rate of transport and adsorption of cells, organic and inorganics to the surface	$(ML^{-2} t^{-1})$
$R_B$ = net biofilm accumulation rate	$(ML^{-2} t^{-1})$
$R_D$ = rate of detachment of biofilm	$(ML^{-2} t^{-1})$
Re = Reynolds Number	(dimensionless)
s = limiting nutrient concentration in bulk water	$(ML^{-3})$

$St_b$	= Stanton Number	(dimensionless)
$T_l$	= temperature at $r_l$	(T)
$T_i$	= temperature in tube wall at $r_i$	(T)
$T_{ii}$	= temperature in tube wall at $r_{ii}$	(T)
$T_b$	= bulk fluid temperature	(T)
$\Delta r$	= biofilm thickness, $r_i - r_I$	(L)
$T_I$	= temperature at $r_I$	(T)
$U_{cond}^{-1}$	= conductive heat transfer resistance	$(M^{-1}t^3T)$
$U_{conv}^{-1}$	= convective heat transfer resistance	$(M^{-1}t^3T)$
$U_{overall}^{-1}$	= overall heat transfer resistance	$(M^{-1}t^3T)$
$v_m$	= mean fluid velocity	$(Lt^{-1})$
$x$	= biomass concentration in bulk water	$(ML^{-3})$
$Y$	= mass of biofilm produced per unit nutrient mass consumed	(dimensionless)
$z$	= length	(L)
$\Delta p$	= pressure drop across length L	$(ML^{-1}t^{-2})$
$\mu$	= fluid viscosity	$(ML^{-1}t^{-1})$
$\rho_f$	= fluid density	$(ML^{-3})$
$\rho$	= biofilm density	$(ML^{-3})$
$\tau_w$	= fluid shear stress at biofilm surface	$(ML^{-1}t^{-2})$
$\delta_l$	= viscous sublayer thickness	(L)
$\epsilon$	= effective height of roughness element	(L)

## INTRODUCTION

The term fouling refers to the undesirable formation of inorganic and/or organic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase the fluid frictional resistance at the surface, and increase the rate of corrosion at the surface. In each case, energy loss results.

Several types of fouling and their combinations may occur in heat exchangers: (1) crystalline or precipitation fouling, (2) corrosion fouling, (3) particulate fouling, (4) chemical reaction fouling, and (5) biological fouling or biofouling. Biological fouling results from (a) development of an organic film (biofilm) consisting of microorganisms and their products (microbial fouling), (b) deposition and growth of macroorganisms such as barnacles (macrobial fouling), and (c) assorted detritus. Although many different macroorganisms such as barnacles and mussels have been identified in fouling communities, this paper will concentrate on microbial fouling assuming that it always precedes colonization of the surface by macroorganisms. Based on this premise, control of microbial fouling results in control of macrobial fouling.

Biofouling is not limited to microbial activity. The term includes the interaction of the microorganisms and the slime layer with both the chemistry of the solid surface and the bulk fluid. The interaction can enhance some of the more commonly known phenomena such as precipitation or crystallization (scaling) and corrosion. Fouling biofilms form on condenser surfaces reducing heat transfer and lowering plant efficiency (Purkiss, 1972; Ritter and Suitor, 1976).

Relatively little effort has been invested in mechanistic studies relating biofilm development to heat transfer resistance. This paper describes a more fundamental approach focused on the influence of fouling deposits, primarily biofilms, on heat transfer.

## Measurement of Energy Losses due to Fouling Deposits

Real time monitoring of fouling in the laboratory or at a power generation site would be extremely valuable if at least two quantities could be determined:

- (1) Extent of fouling
- (2) Composition of fouling deposit

An instantaneous measure of the extent of fouling could be used to determine its influence on power production. The deposit composition would be invaluable in deciding upon an appropriate remedial treatment. Traditionally, water quality parameters (chemical analysis, selective ion electrodes and bacterial counts) have been used to predict fouling potential and determine treatment. However, these parameters define conditions in the bulk water which generally are significantly different from surface conditions where the problem exists. More recently, fouling monitors have been developed which indicate the effects of a fouling deposit on frictional resistance and heat transfer resistance. These measurements, however, yield no information regarding the composition of the deposit. One of our goals is to develop a comprehensive fouling monitor system to determine the rate and extent of fouling and the type of fouling deposit so that appropriate treatment can be applied.

Fouling deposits are rarely homogeneous. Generally, the fouling deposit is a combination of biofilm, scale and corrosion products. The degree to which each type of deposit contributes to fouling is dependent on the reaction environment. Basic differences in the effects of scale and biofilms on thermohydrodynamic measurements, in conjunction with water quality measurements, can provide useful insight to distinguishing between scale and biofilm, particularly once a history of heat exchanger performance has been established.

## A Fouling Monitor

A fouling monitor system has been used to monitor biofouling, its influence on heat transfer, and to experimentally determine the usefulness of mathematical models. At present, the fouling monitor system consists of three major components (Figure 1):

1. The tubular reactor contains a heat transfer section consisting of an electrically heated aluminum block clamped around the tube. The block contains two temperature probes. The tube can be of any relevant alloy and is interchangeable. The tube contains ports for pressure drop measurement. The reactor also includes a flow meter, a motorized valve, and a bulk water temperature probe. Figure 2 is a schematic diagram of the heat transfer section.
2. A microcomputer calculates frictional resistance, convective heat transfer resistance (HTR), conductive HTR, and overall HTR. The microcomputer can also control the following:

frictional resistance or flow rate

heat flux or inside tube surface temperature

Output from the microcomputer includes a television monitor for display and a cassette recorder to establish historical records.

3. A micrometer device provides a measure of deposit thickness.

Frictional resistance is determined from pressure drop and flow measurements in the tube. The relative roughness of the deposit can be determined from friction factor and average deposit thickness. Overall heat transfer resistance is calculated from measurement of bulk water temperature and temperatures in the aluminum block. Convective heat transfer resistance is dependent on turbulence and is calculated from the friction factor and properties of water. Conductive heat transfer resistance is the difference between

overall HTR and convective HTR. Deposit thermal conductivity can be determined if deposit thickness is measured.

The monitor accomplishes the following:

- (1) The extent of fouling can be instantaneously reported in terms of fluid frictional resistance, overall heat transfer resistance, and deposit thickness. This information can also serve as an early warning of fouling problems.
- (2) Historical data can be retrieved to determine the influence of environmental factors (e.g., temperature, water quality, fluid shear stress) on the rate of deposit accumulation.
- (3) Characteristics of the deposit (roughness and thermal conductivity) can be obtained in situ instantaneously and used to estimate the deposit composition. Deposit composition dictates which remedial measure is applied.

#### FOULING BIOFILM FORMATION

Development of a systematic understanding of biofouling from field observations has been limited because of the interaction of several contributing rate processes. Mechanistically, fouling biofilm accumulation may be described as the net result of the following:

- Transport of material from the bulk fluid to the surface and adhesion to the surface. Transported materials can be soluble (microbial nutrients and organic salts) or particulate (viable microorganisms, their detritus, or inorganic particles). Fouling begins once these materials adhere to the surface. Suspended particles of sufficient mass may also control films by "scouring" action.
- Microbial reactions within the film. Microbial growth in the biofilm and extracellular polymers produced by the microorganisms contribute



to biofilm accumulation and promote adherence of inorganic suspended solids.

- Fluid shear stress at the surface of the film. Such forces can limit the overall extent of the fouling deposit by removing attached material.
- Surface material and roughness. Surface properties can influence micro-mixing near the surface and corrosion processes. Some metal surfaces may release toxic components into the biofilm inhibiting growth and/or attachment. Some metals produce loosely held oxide films under the biofilms. When the oxide film sloughs the biofilm is also removed.
- Fouling control procedures. Chlorine, the most commonly used chemical, oxidizes biofilm polymers causing disruption and partial removal of biofilm in the fluid shear stress field. Inactivation of a portion of the microbial population also occurs. Altered biofilm "roughness" and decreased viable cell numbers influence "regrowth" rates of the biofilm. Mechanical cleaning physically removes a portion of the biofilm.

#### Mathematical Model of Fouling Biofilm Formation

A mathematical model simulating fouling biofilm development and its influence on heat transfer will be described. The model may be useful for several purposes including the following (after Himmelblau and Bischoff, 1968):

- Economical experimentation: fouling processes can be studied more quickly and economically than possible in the laboratory or field.
- Extrapolation: extreme ranges of operating conditions can be tested which may be impractical otherwise.
- Evaluation of alternative policies: various designs, operating procedures and treatment processes can be tested before decisions are made.

- Design of experiments: the model indicates the variables to be measured and the data that must be provided for useful evaluation procedures.
- Test of sensitivity: the model can indicate which parameters have a significant influence on process behavior.

However, one significant limitation of modelling must be recognized. The success of the model depends heavily on the basic information available. The model is only as accurate as the physical, chemical, and biological data that go into the model.

Fouling biofilm development is the net result of several physical, chemical and biological processes including the following (Figure 3):

- transport and adsorption of inorganic and organic molecules at the wetted surface
- transport of microbial cells and other particulate material to the wetted surface
- adsorption and microbial adhesion to the surface
- microbial reactions within the biofilm
- detachment of portions of the deposit by fluid shear

Net biofilm accumulation rate,  $R_B$ , reflects a combination of all the rate processes above:

$$R_B = R_A + \text{NAY} - R_D \quad (1)$$

Net biofilm accumulation rate = rate of transport and adsorption of cells + rate of biofilm production at the surface - rate of biofilm detachment from the surface

Net rate of transport and adsorption has been described by Fletcher (1977) as follows:

$$R_A = k_A \times \left(1 - \frac{\rho Th}{k_A'}\right) \quad (2)$$

The rate of biofilm production due to nutrient consumption,  $N_Y$ , has been experimentally determined by Trulear and Characklis (1981) as follows:

$$N_Y = \frac{k_p \rho Th s}{k'_p + s} \quad (3)$$

The rate of biofilm detachment due to fluid shear,  $R_D$ , has been experimentally determined by Trulear and Characklis (1981). An approximate expression can be derived from their data as follows:

$$R_D = \rho Th k_D \exp(k'_D \tau_w) \quad (4)$$

Figure 4 depicts the progression of biofilm thickness and net biofilm accumulation rate ( $R_{B,A}$ ) from the time a clean surface is immersed in a fouling environment.  $R_{B,A}$  is the sum of all the individual processes described above.

#### Influence of Environmental Factors on Process Rate

Among the environmental factors affecting fouling biofilm formation rate, specific data are available on the following:

- (1) dispersed microbial cell concentration in the bulk liquid (Fletcher, 1977; Bryers and Characklis, 1981)
- (2) limiting nutrient concentration (Trulear and Characklis, 1981)
- (3) fluid shear stress at the liquid-solid interface (Bott and Pinheiro, 1977; Bryers and Characklis, 1981; Trulear and Characklis, 1981).
- (4) temperature (Characklis, 1980; Stathopoulos, 1981; Bott and Pinheiro, 1977)
- (5) characteristics of substratum surface (Dexter, 1976; Loeb and Neihof, 1975; Fletcher and Loeb, 1979).

In a eutrophic environment (high cell and nutrient concentration), biofouling rates are high. Biofouling increases with temperature up to some critical temperature dictated by the microorganism species present. Above this critical temperature, biofouling rate decreases. Fluid shear stress increases

detachment rate from the biofilm and, hence, decreases biofouling rate. However, if liquid phase mass transfer is controlling biofilm nutrient removal or transport of cells to the surface, shear stress will increase the rate of biofouling. Characteristics of the substratum surface are important in the adhesion process. Wettability, or critical surface tension, is the property used most frequently to describe surface characteristics in microbial attachment studies. In seawater, cell attachment increases with increasing critical surface tension (glass, copper, polyethylene, teflon) with the exception of copper. The macro- and microroughness of the substratum all influence biofouling rates. Roughness influences rate of transport to the substratum of cells and nutrients. Roughness elements partially shield cells at the surface from fluid shear stress and increase the effective area for adsorption.

#### Other Factors Influencing Accumulation Rate

Fouling may result from processes other than those related to microbial activity. Crystallization (scaling), sedimentation, and corrosion are acknowledged as severe fouling problems. Fouling accumulation on a heated surface is most probably the net result of all these processes. Specific environmental conditions dictate which process is dominant at any given location and time. For example, the surface may initially be too hot for microbial activity but crystallization may occur. As the crystalline deposit accumulates, the surface temperature decreases to a range suitable for microbial activity and biofouling begins.

Suspended or particulate material in the water also can influence accumulation rate. Light, small particles in a low velocity flow adsorb easily to the "sticky" biofilm surface increasing the accumulation rate. Heavier, larger particles in a highly turbulent flow can scour the surface, thus reducing the rate of accumulation.

## INFLUENCE OF BIOFILMS ON FLUID FRICTIONAL RESISTANCE

Fouling deposits cause increased fluid frictional resistance by decreasing the effective diameter of the heat exchange tube and by increasing tube roughness. Biofilms increase fluid frictional resistance primarily by increasing the effective roughness of the tube.

### Process Description

Picologlou et al (1980) have experimentally determined the influence of biofilm on fluid frictional resistance in a tube. Increase in frictional resistance and calculated equivalent sand roughness correspond to an increase in biofilm thickness or biofilm mass. The increase in frictional resistance is characterized by an induction period at small biofilm thickness followed by a rapid increase after biofilm reaches a critical thickness. The critical biofilm thickness corresponds to the viscous sublayer thickness calculated for clean tube conditions. Characklis et al (1981) present data confirming these observations for varying fluid velocities. Filamentous organisms, if present in the biofilm to a significant extent, increase frictional resistance much more than non-filamentous organisms (Trulear and Characklis, 1981).

Constriction of the tube due to biofilm accumulation only constitutes a small fraction (approx. 10%) of the observed frictional resistance (Picologlou et al, 1980). In contrast to biofouling accumulation, calcareous deposits constrict the tube to a significant extent (Cowan and Weintritt, 1976). The biofilm is viscoelastic (Characklis, 1980), a factor which may also influence fluid frictional resistance (Schuster, 1971).

Regardless of the mechanisms causing the unexpectedly high frictional resistance, the effect of Reynolds number (from 5,000 - 48,000) on friction factor (e.g., Moody Diagram) for a tube with an attached biofilm is similar to a tube with a rigid rough surface (Figure 5).

### Mathematical Model for Frictional Resistance due to Biofouling

Picologlou et al (1980) have experimentally determined the influence of biofilm on fluid frictional resistance. For a given biofilm thickness, friction factor ( $f$ ) was independent of Reynolds number ( $Re$ ) for  $Re > 10,000$  when  $Th$  exceeded the viscous sublayer thickness  $\delta_1$ . However,  $f$  was a function of biofilm roughness ( $\epsilon$ ). Therefore, the following expression describes the dimensionless friction factor in a tube when  $Th > \delta_1$  (Davies, 1972):

$$f = 1.13 - 0.87 \ln\left(\frac{\epsilon}{2r_I}\right)^{-2} \quad (5)$$

Friction factor for any thickness and roughness is described by:

$$f = \frac{4r_I}{L} \frac{\Delta p}{\rho_f v_m^2} \quad (6)$$

### Other Factors Influencing Fluid Frictional Resistance

A condenser contains hydraulically smooth tubes when installed. After a period of operation, the tubes generally become hydraulically rough as a result of corrosion, erosion, and inorganic deposition. Picologlou et al (1980) have described results of experiments comparing biofouling in smooth and pre-roughened tubes. Under identical conditions, initial frictional resistance will be significantly higher in the pre-roughened tube. The frictional resistance in the pre-roughness' tube remained significantly higher throughout the development of a fouling biofilm. Therefore, a rough tube results in even higher energy losses than in a smooth tube when biofouling occurs.

### INFLUENCE OF BIOFILMS ON HEAT TRANSFER RESISTANCE

Overall heat transfer resistance is the sum of conductive and convective heat transfer resistances. Convective heat transfer resistance will decrease as fouling progresses due to the increased turbulence as evidenced by a higher friction factor. Conductive heat transfer resistance will increase

as the thermal insulating fouling deposit accumulates. The relative magnitude of changes in convective and conductive heat transfer resistance due to the deposit will depend on the following:

- properties of the deposit such as thickness, roughness and thermal conductivity
- fluid flow rate (more fundamentally, shear stress at the wall)

Process Description

Heat transfer rate in a tube is generally described in terms of an overall heat transfer coefficient (U). The inverse of the overall heat transfer coefficient ( $U^{-1}$ ) is the overall heat transfer resistance (HTR). Resistances are additive and, therefore, are convenient to this discussion. Overall HTR can be considered the sum of convective HTR and conductive HTR:

$$U^{-1} = \frac{r_i l}{r_I h} + r_i \frac{\ln(r_l/r_I)}{k_B} + r_i \frac{\ln(r_i/r_l)}{k_t} \quad (7)$$

overall	convective		conductive		conductive
heat	heat trans-		heat trans-		heat trans-
transfer	fer resis-	+	fer resis-	+	fer resis-
resistance	tance		tance in the		tance in
			biofilm		the tube

The convective heat transfer coefficient, h, can be determined by measuring the temperature differential between the biofilm-fluid interface and the bulk fluid. Such an effort is presently impractical due to difficulties in making accurate, nondisruptive temperature measurements at the biofilm-fluid interface. The relation between momentum transfer and heat transfer in turbulent flow provides an alternate means of determining the convective heat transfer coefficient.

Colburn (1933) analyzed data on convective heat transfer and pressure drop in a tube from a large number of experiments and found it possible to predict the heat transfer coefficient from the friction factor. Expressed

in terms of the Stanton number, the Colburn relationship is:

$$St_b Pr_f^{2/3} = f/8 \quad (8)$$

The Stanton number is based on properties of the fluid at bulk temperature while the Prandtl number and friction factor are based on properties evaluated at the arithmetic mean of the bulk temperature and temperature at the fluid-solid interface. The solid may be the clean tube surface or the biofilm. The Colburn relationship applies to flows with Reynolds numbers in excess of 10,000 and may be applied as an approximation in hydraulically rough tubes (Kirkpatrick et al, 1980). Consequently, the convective HTR ( $h^{-1}$ ) can be determined from fluid properties, fluid velocity and friction factor data.

The conductive HTR due to biofilm accumulation requires measurement of biofilm thickness ( $Th = r_1 - r_I$ ) and biofilm thermal conductivity. Measurements indicate that biofilm thermal conductivity is not significantly different from water (Characklis et al, 1981).

Figure 6 describes the progression of conductive; convective and overall HTR as a fouling biofilm accumulates.

#### Mathematical Model for Heat Transfer Resistance due to Biofouling

Modelling overall heat transfer resistance due to fouling biofilm development requires the following:

1. a model of biofilm development because it directly influences frictional resistance and conductive HTR.
2. a model for frictional resistance as a function of biofilm accumulation because it directly influences convective HTR.

Model equations for biofilm development and frictional resistance have been presented. The convective heat transfer coefficient can be determined from Eq. (8) and rearranged to yield



$$h = 0.125 f C_p^{0.33} \mu^{-0.67} k^{0.67} \rho_f V_m \quad (9)$$

Then convective heat transfer resistance,  $U_{\text{conv}}^{-1}$ , can be expressed as

$$U_{\text{conv}}^{-1} = \frac{r_i}{r_I} \frac{1}{h} \quad (10)$$

Conductive heat transfer resistance due to biofilm accumulation,  $U_{\text{cond}}^{-1}$ , is described by the following:

$$U_{\text{cond}}^{-1} = \frac{r_i}{k_B} \ln \left( \frac{r_1}{r_I} \right) \quad (11)$$

Figure 7 diagrammatically describes the model for overall heat transfer resistance due to fouling biofilm development.

#### Other Factors Influencing Heat Transfer Resistance

Deposits, other than biofilms, may form on heat exchange surfaces. Inorganic deposits composed of calcium, magnesium, silica, and iron may form on the surface as a result of chemical precipitation and corrosion and cause increased HTR. Repeated chlorination may result increased corrosion rates. Repeated chlorination may also result in the formation of a relatively inert inorganic deposit in seawater (Mangum et al, 1973) and in a laboratory freshwater system (Characklis, 1980) which may also influence HTR.

In addition, particulate material suspended in the cooling water may influence heat transfer. Small particles (e.g., sand, silt, clay) adsorb readily to a surface conditioned by biofilm changing the effective thermal conductivity of the deposit. For example, the thermal conductivity of sand is approximately one half that of biofilm. On the other hand, large particles in high concentrations may scour the surface and thus help maintain a clean surface (Bour, 1979).

## SUMMARY

Biofilm development and its influence on fluid frictional resistance and heat transfer resistance has been described in conceptual and mathematical models. References have been provided to experimental and field data which influenced the formulation of the models. An experimental system for determining the extent of energy losses resulting from fouling has been described. The system can provide information from in situ measurements regarding the composition of the deposit. The experimental system can be used in the laboratory or in the field to test the influence of environmental factors on the rate and extent of fouling.

#### REFERENCES CITED

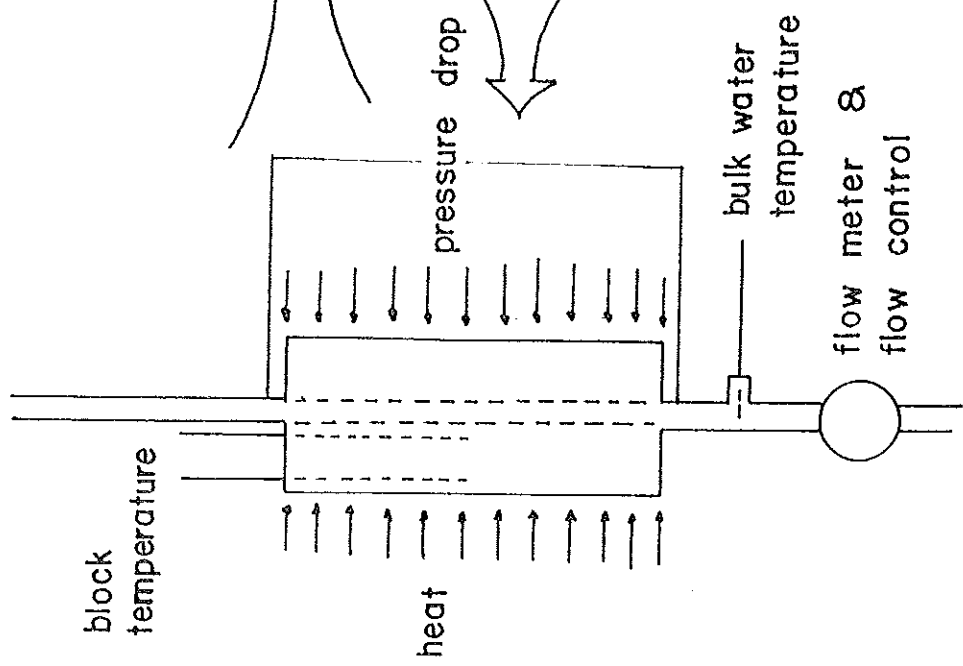
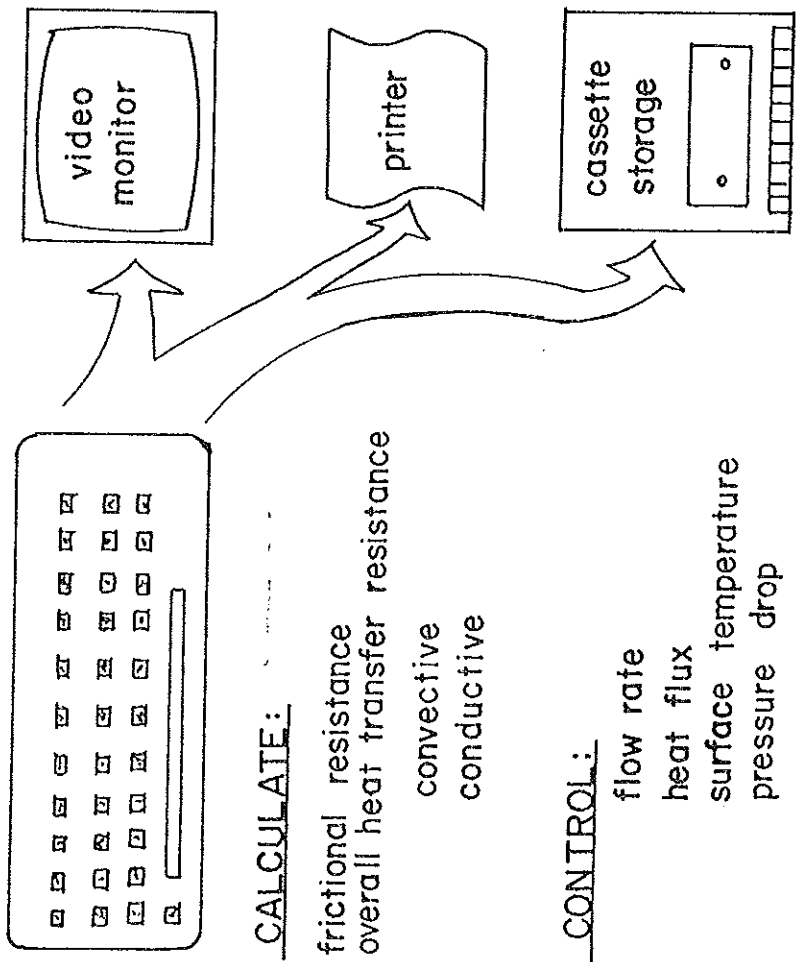
- Bott, J. R. and M. M. V. P. S. Pinheiro. 1977. Biological Fouling Velocity and Temperature Effects. *Can. J. Chem. Engng.* 55:473-474.
- Bour, D. P. 1980. Biofouling Experience and Practices on Once-Through Condensers at Electric Generation Stations. *Proc. Condenser Biofouling Control Symposium.* 267-277 pp. ed. J. F. Garey, et. al. Ann Arbor. Ann Arbor Science Publishers, Inc.
- Bryers, J. and Characklis, W. G. 1981. Early Fouling Biofilm Formation in Turbulent Flow System: Overall Kinetics. *Wat. Res.* 15:483-491
- Characklis, W. G. 1980. Biofouling Film Development and Destruction. EPRI. RP902-1.
- Characklis, W. G., Nimmons, M. J., and Picologlou, B. F. 1981. Biofilm Development and Heat Transfer. Accepted by *Heat Transfer Engineering.*
- Colburn, A. P. 1933. A Method of Correlating Forced Convection Heat Transfer Data and Comparison With Fluid Friction. *Trans. Am. Inst. Chem. Engrs.* 29:139.
- Cowan, J. C. and Weintritt, D. J. *Water-formed Scale Deposits.* 596 pp. Houston: Gulf Publishing Company. 1976.
- Davies, J. J. *Turbulence Phenomena.* New York: Academic Press. 1972.
- Dexter, S. C. 1976. Influence of Substrate Wettability on the Formation of Bacterial Slime Films on Solid Surfaces Immersed in Natural Sea Water. *Proc. 4th Int'l. Congress on Marine Corr. and Fouling,* Juan-Les-Pins, Antibes, France.
- Fletcher, M. 1977. The Effect of Culture Concentration and Age, Time, and Temperature on Bacterial Attachment to Polystyrene. *Can. J. Microbiol.* 23:1-6.
- Fletcher, M. and G. I. Loeb. 1979. Influence of Substratum Characteristics on the Attachment of a Marine Pseudomonad to Solid Surfaces. *Appl. Env. Microbiol.* 37:67-72.
- Himmelblau, D. M., and Bischoff, K. B. *Process Analysis and Simulation.* New York: John Wiley and Sons. 1968.
- Kirkpatrick, J. P., McIntire, L. V. and Characklis, W. G. 1980. Mass and Heat Transfer in Circular Tube With Biofouling. *Wat. Res.* 14:117.
- Loeb, G. I. and R. A. Neihof. 1975. Marine Conditioning Films. *In: Applied Chemistry at Interfaces.* p.p. 319-335, *Adv. Chem. Ser.* 145, ACS, Washington, D. C.

- Mangum, D. C. and B. P. Shepherd. 1973. Methods of Controlling Marine Fouling in Seawater Desalination Plants. Final report submitted to the Office of Saline Water, U. S. Dept. of Interior by the Dow Chemical Co., Contract No. 14-30-2829.
- Picologlou, B. J., Zilver, N. and Characklis, W. G. 1980. Biofilm Growth and Hydraulic Performance. Proc. Am. Soc. Civ. Engrs. 106:733-746.
- Purkiss, B. E. Biotechnology of Industrial Waste Conservation. London: M&B Monographs, Mills and Boon. 1972.
- Ritter, R. B. and Sutor, J. W. 1976. Fouling Research on Copper and Its Alloys - Seawater Studies. HTRI Progress Report. INCRA Project No. 214A.
- Schuster, H. 1971. Fluid Friction in the Presence of Nonrigid Boundaries. Ph.D. Thesis, John Hopkins University, Baltimore.
- Stathopoulos, N. 1981. Influence of Temperature on Biofilm Process. M.S. Thesis. Rice University, Houston.
- Trulear, M. G., Characklis, W. C. 1981. Dynamics of Biofilm Process, accepted for publication, J. Wat. Pollut. Control Fed.

# FOULING MONITOR

# MICROCOMPUTER

# OUTPUT

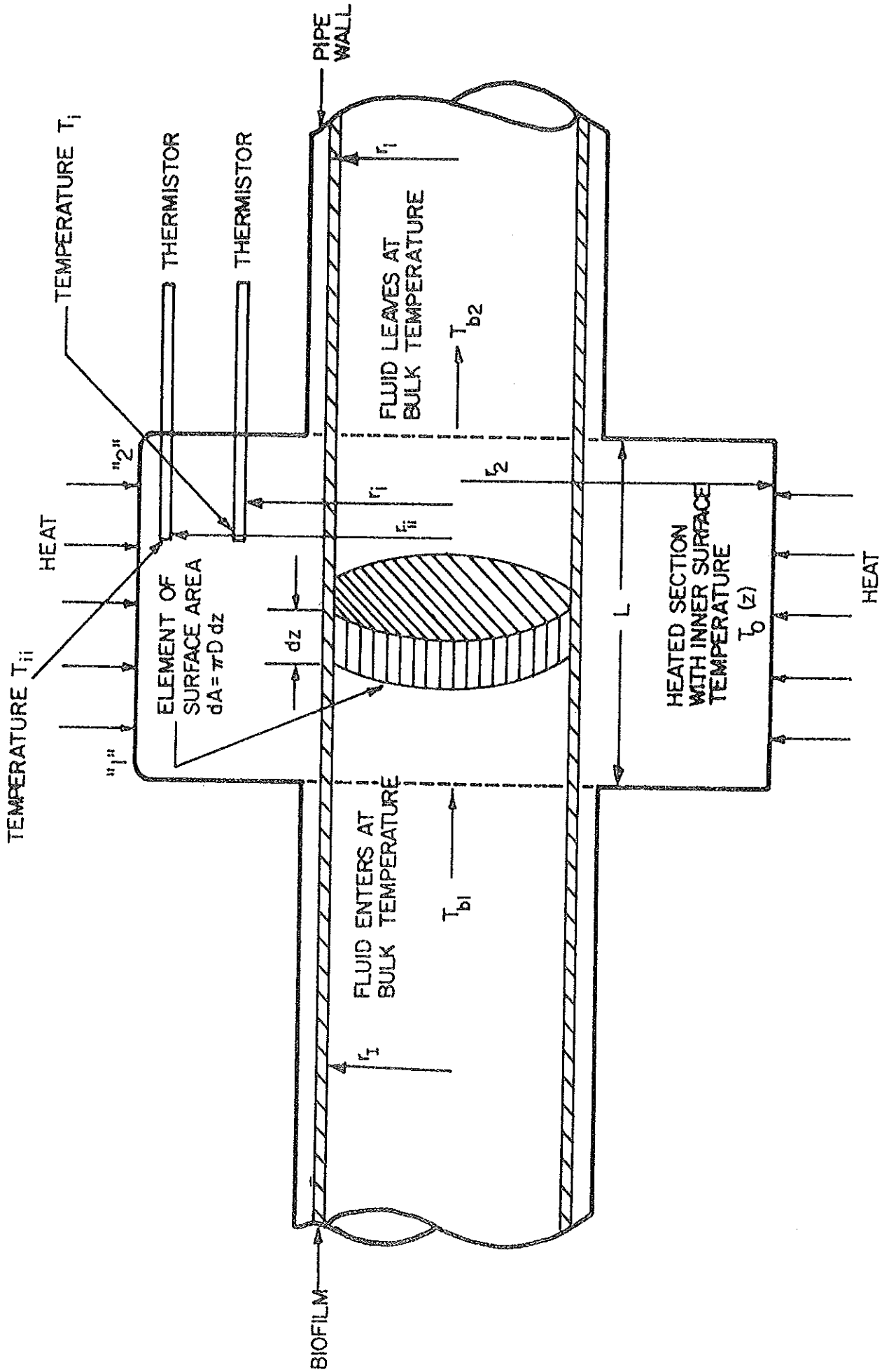


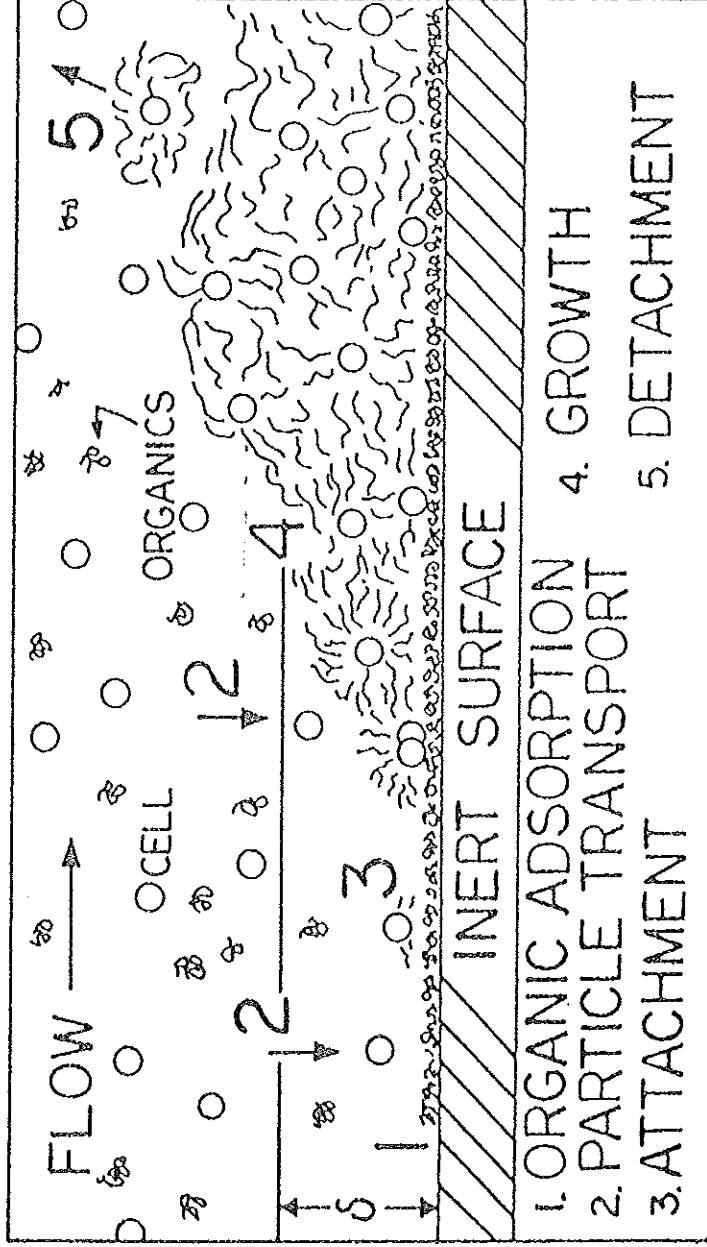
## CALCULATE:

- frictional resistance
- overall heat transfer resistance
- convective
- conductive

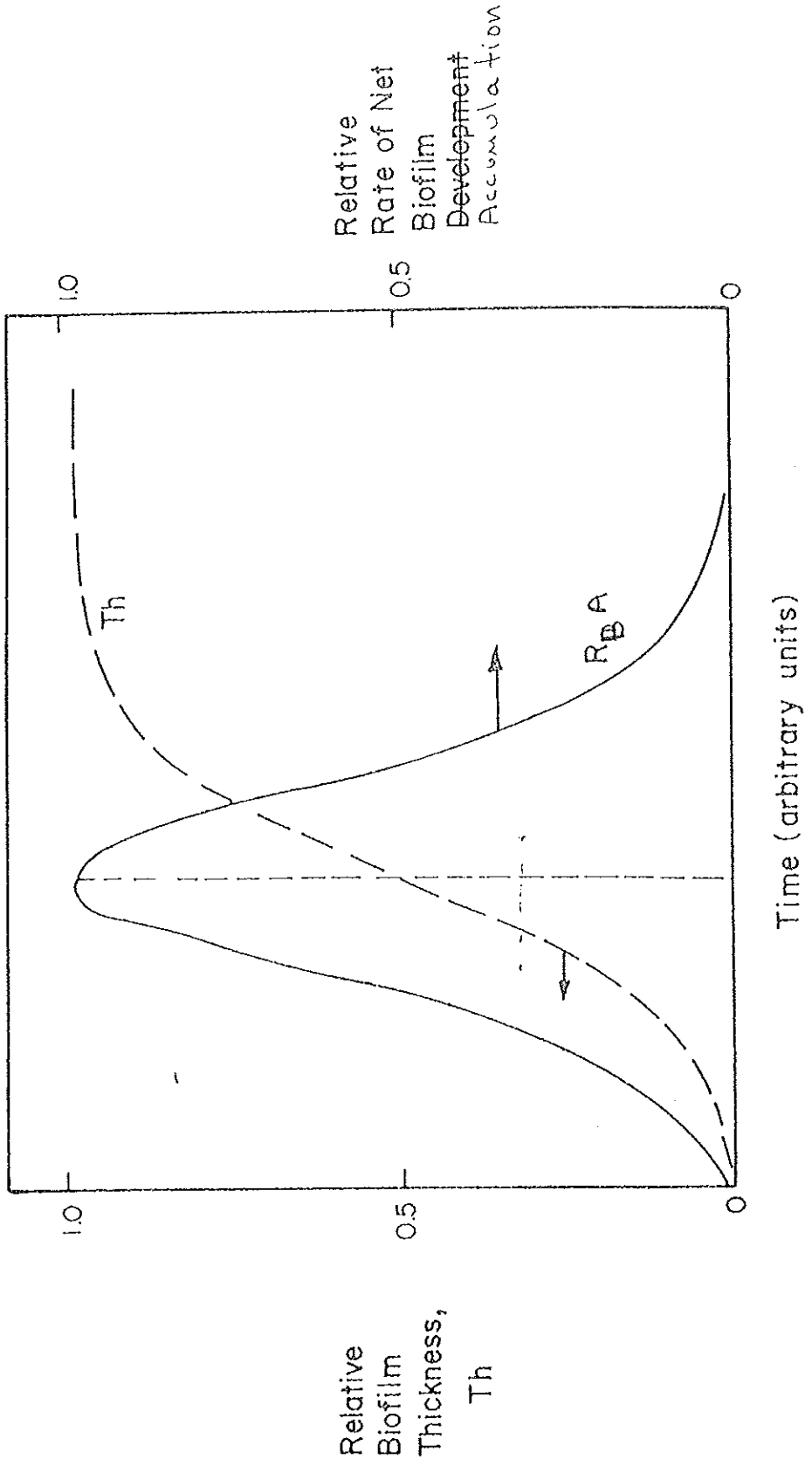
## CONTROL:

- flow rate
- heat flux
- surface temperature
- pressure drop

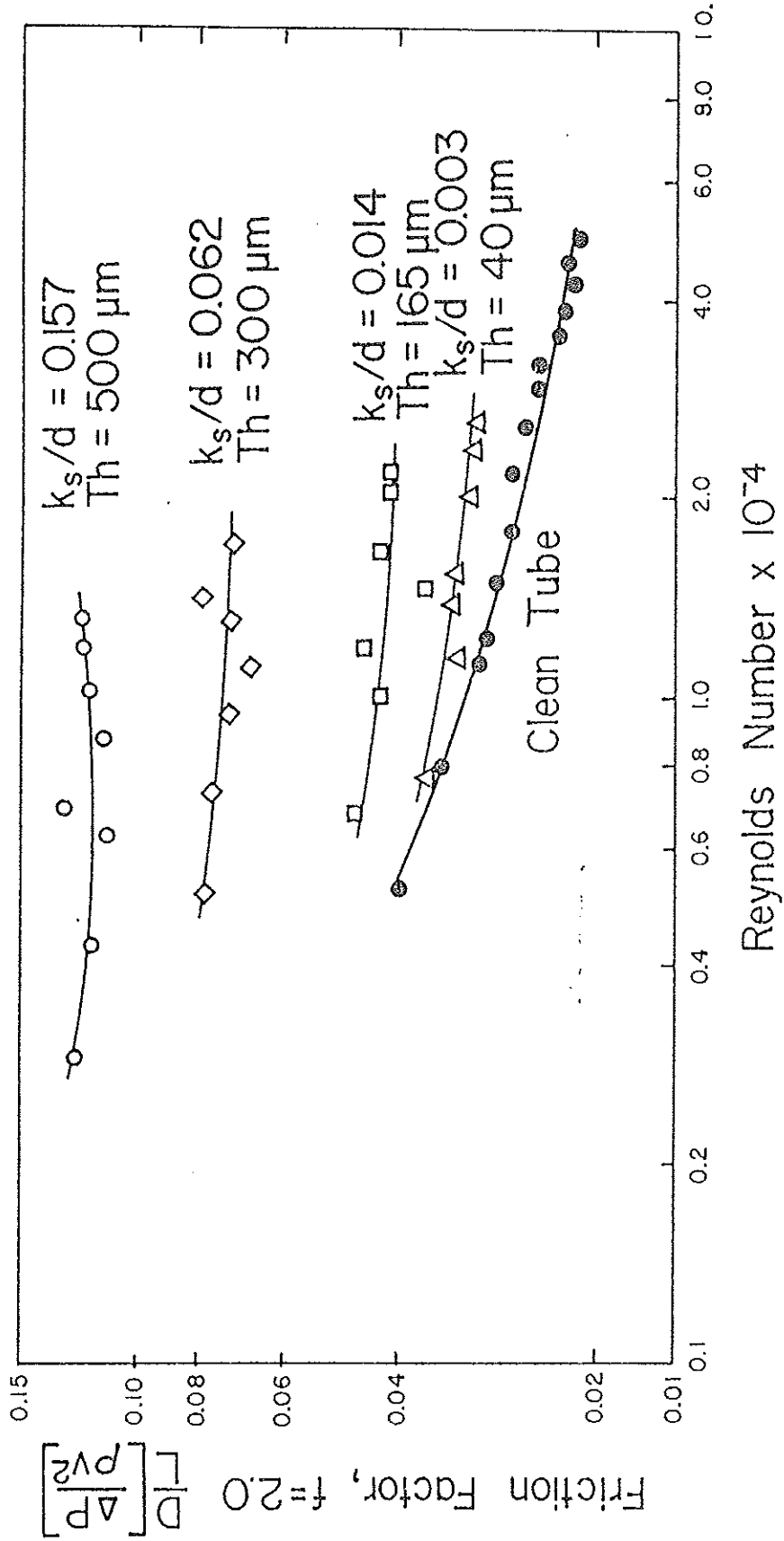




## BIOFOULING PROCESSES







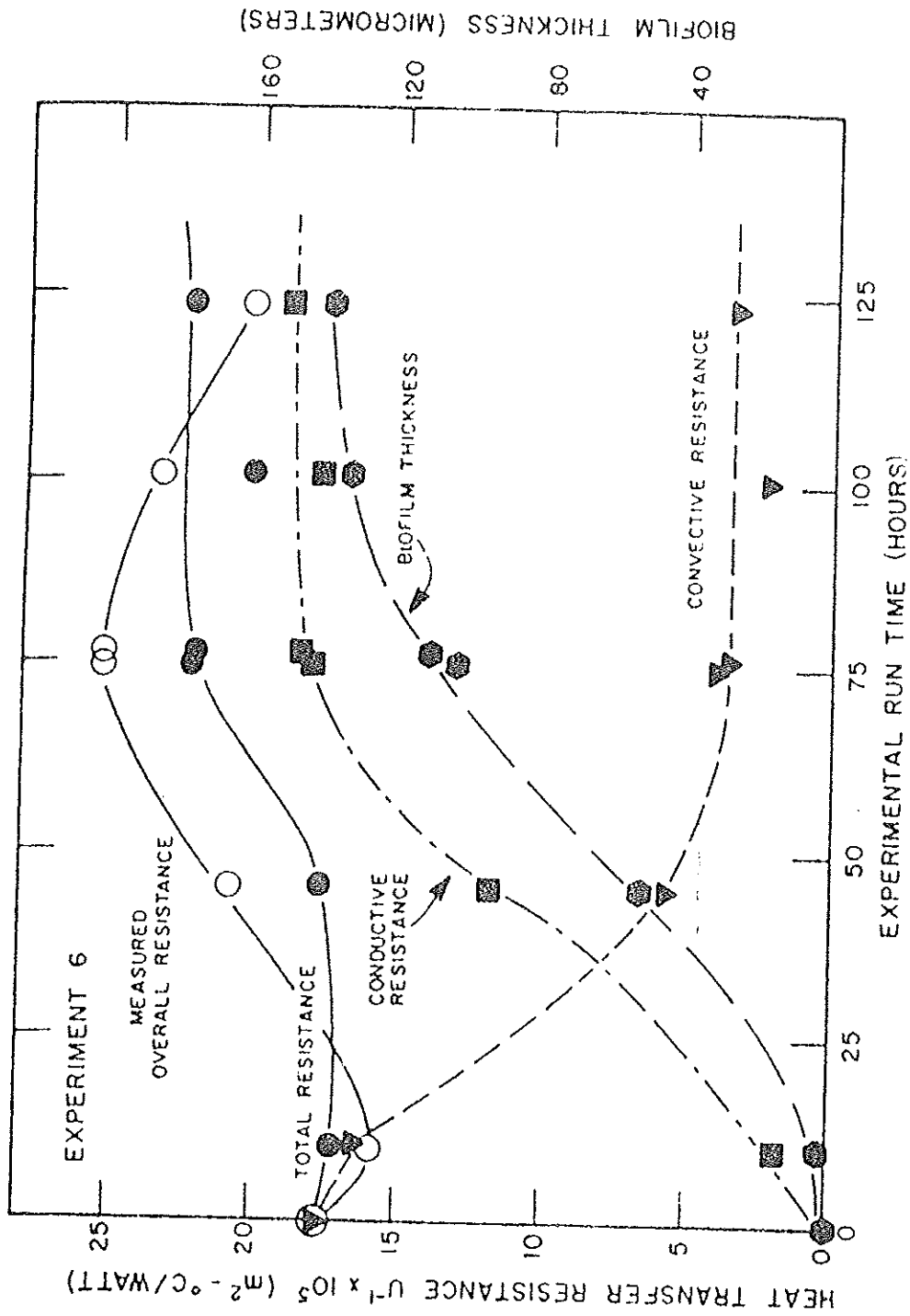


Figure 19. Changes in Heat Transfer Resistance as a Result of Biofilm Accumulation

$R_A$   $\rightarrow$   $A$   $\rightarrow$   $N$   $\rightarrow$   $Y$   $\rightarrow$   $R_D$   $\rightarrow$

**BIOFILM GROWTH**

$$R_{BL}^A = R_A A + NAY - R_D A$$

$T_H$   $\rightarrow$

$r_1$   $\rightarrow$   $K_B$   $\rightarrow$   $r_2$

**CONDUCTIVE RESISTANCE**

$$U_{COND}^{-1} = \frac{r_2 \text{LN} (r_1 / r_2)}{K_B}$$

$U_{COND}^{-1}$

$T_H$   $\rightarrow$   $\epsilon$   $\rightarrow$

**OVERALL HEAT TRANSFER RESISTANCE**

$$U_{OVERALL}^{-1} = U_{COND}^{-1} + U_{CONV}^{-1}$$

$U_{OVERALL}^{-1}$

**FRICTIONAL RESISTANCE**

$$T_H \leq \delta_1 ; = 0.316 / Re^{0.25}$$

$$T_H > \delta_1 ; = (1.13 - 0.87 \text{LN} (\epsilon / 2r_1))^{-2}$$

$f$   $\rightarrow$

**CONVECTIVE RESISTANCE**

$$h = 0.125 f^{0.5} C_p^{0.33} \mu^{-0.67} k^{-0.67} \rho^{0.67} v_M$$

$$U_{CONV}^{-1} = \frac{1}{h} = \frac{\mu}{k} \frac{1}{f^{0.5} C_p^{0.33} \rho^{0.67} v_M}$$

$U_{CONV}^{-1}$

$\delta_1$   $\rightarrow$   $Re$   $\rightarrow$   $r_1$

$C_p$   $\rightarrow$   $\mu$   $\rightarrow$   $k$   $\rightarrow$   $\rho$   $\rightarrow$   $v_M$   $\rightarrow$   $r_2$