



The effect of velocity variation on cooling tower water heat transfer fouling
by Mukesh Harilal Turakhia

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
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Abstract:

Fouling refers to the deposition of undesirable materials on heat exchanger surfaces. Fouling from cooling tower water is a serious problem in both power and chemical process industries. Experiments were carried out to study the possibility of using high velocity flush out as a method of controlling fouling using simulated cooling tower water. The bulk temperature and the heat flux were kept constant.

The results are reported in the form of fouling resistance, R_f , as a function of time. It was concluded that high velocity flush out was not effective for the system studied.

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ON
COOLING TOWER WATER HEAT TRANSFER FOULING
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A thesis submitted in partial fulfillment
of the requirements for the degree
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Approved:

William Jenetta
Chairperson, Graduate Committee

J.P. McCallister
Head, Major Department

Henry L. Parsons
Graduate Dean

MONTANA STATE UNIVERSITY
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ABSTRACT

Fouling refers to the deposition of undesirable materials on heat exchanger surfaces. Fouling from cooling tower water is a serious problem in both power and chemical process industries. Experiments were carried out to study the possibility of using high velocity flush out as a method of controlling fouling using simulated cooling tower water. The bulk temperature and the heat flux were kept constant.

The results are reported in the form of fouling resistance, R_f , as a function of time. It was concluded that high velocity flush out was not effective for the system studied.

INTRODUCTION

Fouling refers to any undesirable deposit on a heat exchanger surface that will increase the resistance to heat transmission. The chemical and process industries use large quantities of cooling water. In United States this usage (1) comprises about one third of the total water consumption for all purposes. Cooling water fouling of heat exchange equipment is a serious problem in both the electrical power and the chemical process industries. In fact, the magnitude of the problem is so great that fouling (2,3) has been referred to as the major unresolved problem in heat transfer.

Cooling water fouling may be caused by deposition of suspended solids, by microbial growth, by corrosion products and/or by crystalline deposits. In a commercial application it is usually a combination of these processes.

The most important process is the deposition of salts having inverse solubility characteristics. Such salts can be saturated or even unsaturated at bulk conditions but can be highly supersaturated on a hot surface area. Among the salts which have inverse solubility characteristics are calcium carbonate, calcium sulfate and some forms of silicon salts.

Table I shows the composition of cooling tower water from various sources. It can be clearly seen that the quality of water

varies from place to place. Crystallization is also associated with the deposition of suspended particles and corrosion, giving rise to loose crystalline deposits.

The fouling characteristics of a fluid in contact with a heat transfer surface are a function of a variety of parameters:

- (1) Geometry of heat transfer surface
- (2) Material of heat transfer
- (3) Temperature at interface between fouling liquid and heat transfer surface
- (4) Temperature of deposit
- (5) Velocity past heat transfer surface
- (6) Characteristics of fouling fluid.

Table 1. Cooling water composition from various sources.

	Montana Power Butte	Bozeman	Washington State Power Company	Columbia River Hanford	Missouri River Decatur (IA)	Yellowstone River Livingston
Calcium (as Ca)	207	15	150	20	80	23
Magnesium (as Mg)	205	25	-	4	20	8
Sodium (as Na)	676	0.14	*	1	-	-
Iron (as Fe)	-	-	5	0.1	-	-
Chloride (as Cl)	106	4.5	-	1	11	10
Sulfate (as SO ₄)	2420	33	-	10	190	30
Silica (as SiO ₂)	150	-	-	6	-	21
pH	8	8.4	8.5	8.2	7.7	-
TDS	3964	205	-	90	-	170

* Data not available

3

3

BACKGROUND

Fouling Measurement Techniques

The effect of fouling in terms of fouling resistance is usually accounted (3) for in the design of heat exchange equipment by adding fouling resistances R_{fo} and $\frac{A_o}{A_i} R_{fi}$ to the fundamental equation of the overall heat transfer coefficient as:

$$\frac{1}{U_f} = \frac{1}{h_o} + \frac{A_o}{A_i} \frac{1}{h_i} + R_{fo} + \frac{A_o}{A_i} R_{fi} + R_w \quad (1)$$

The values of R_{fo} and R_{fi} are selected from tables of questionable accuracy with vague information as to the operating condition for which the fouling information was obtained. Often the magnitude of these two terms is of the same order or greater than the sum of other terms. This excess area therefore often accounts for more than half of the required areas and cost of heat exchanger.

Assuming fouling occurs only on the heated side and the surface area are equal Equation (1) becomes

$$\frac{1}{U_f} = \frac{1}{h_o} + \frac{1}{h_i} + R_f + R_w \quad (2)$$

Solving for R_f

$$R_f = \frac{1}{U_f} - \left(\frac{1}{h_o} + \frac{1}{h_i} + R_w \right) \quad (3)$$

The term inside the bracket is the reciprocal of the overall heat transfer coefficient of the initially clean surface U_i

$$R_f = \frac{1}{U_f} - \frac{1}{U_i} \quad (4)$$

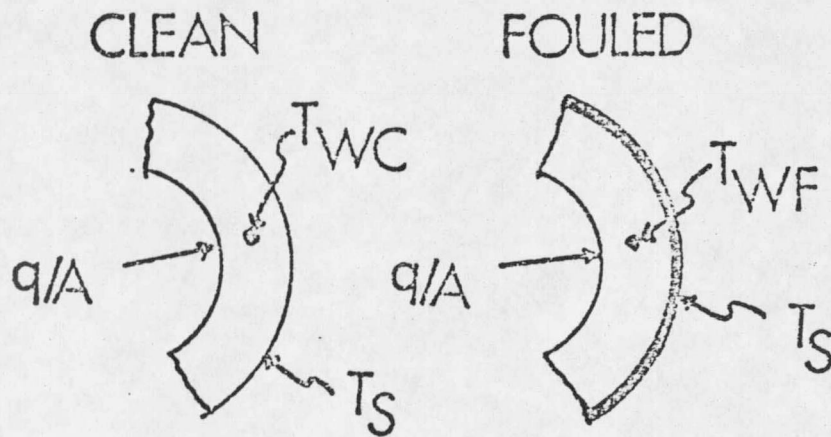


Figure 1. Definition of terms for Data reduction.

Therefore the fouling resistance can be determined by calculating the overall heat transfer coefficient of the clean and fouled tube.

for local fouling measurements, which determines the buildup of fouling at a single locality, the overall coefficient (9) is evaluated by

$$\frac{1}{U} = \frac{T_w - T_b}{q/A} \quad (5)$$

Thus, for a fouling test at constant velocity, heat flux and bulk temperature, the local fouling resistance is calculated as

$$R_f = \frac{T_{wf} - T_{wc}}{q/A} \quad (6)$$

Any change in h_o (due to the change in roughness of the fouled tube) will also change T_{wf} . A definition of terms is shown on Figure 1. To determine the surface temperature, T_s , it is required to know the thermal resistance of the portion of the wall between the thermocouple and tube wall. This thermal resistance can be determined by a Wilson plot (9).

Theoretical Aspects

Fouling rates can be expressed as a function of time with an initial resistance of zero. Two extreme cases in fouling processes are: (1) the fouling deposit continuously increasing with time and (2) asymptotic behaviour. The asymptotic behaviour lends itself to traditional fouling resistance concepts. A fouling resistance which increases with time sets the limit for shut down and cleaning.

Kern and Seaton (6) were first to recognize that a realistic mathematical model for fouling process must be based on material balance:

$$\frac{dR_f}{dt} = \phi_d - \phi_r \quad (7)$$

where dR_f/dt = the net rate of fouling accumulation, ϕ_d the deposition rate and ϕ_r the removal rate. Cooling tower fouling is basically a crystallization process with some noncrystalline sedimentation deposited and trapped in crystal. The deposition rate has been expressed in terms of reaction rate equation, i.e.,

$$\phi_d = kc_r^n \quad (8)$$

The effective reactant concentration, C_r , is a function of the concentrations and of the kind of material in the cooling tower water. The reaction rate constant, k , is an exponential function of the surface temperature. The removal rate, ϕ_r , depends on the hardness or adhesive force of the deposit, on the bond of the deposit to the surface, and on the shearing force, which is a function of the velocity of the system.

The removal rate is proportional to the ratio of shear stress to the bonding resistance of the fouling layer to shear off, that is:

$$\phi_r = C_1 (\tau/R_b) \quad (9)$$

Fouling deposits are sheared off by the fluid at planes of weakness. The probability of the presence of a weak plane is proportional to the thickness of the deposit. Therefore, the bond resistance can be expressed as follows:

$$R_b = \Psi \left(\frac{1}{x_f}\right)^m \quad (10)$$

where Ψ is a proportional constant and is a function of deposit structure. If the discussion is limited to cooling tower water, Ψ will be a function of flow velocity, composition and character of the suspended solids. Substituting 8, 9, and 10 into 7 gives

$$\frac{1}{K_f} \frac{dx_f}{d\theta} + \frac{C_i \tau x_f}{\Psi} = KCr^n \quad (11)$$

Solving,

$$R_f = \frac{x_f}{K_f} = A \exp\left(\frac{-C_i K_f \theta}{\Psi}\right) + \frac{KC_r^n \Psi}{C_i \tau K_f} \quad (12)$$

$$\text{IC } R_f = 0; \quad \theta = 0$$

Therefore,

$$A = -\frac{KC_r^n \Psi}{C_i \tau K_f} = R_{fo}^* \quad (13)$$

$$R_f = R_{fo}^* (1 - e^{-B\theta}) \quad (14)$$

where

$$B = C_i \frac{\tau K_f}{\Psi} \quad (15)$$

As seen from equation (13), the asymptotic fouling resistance R_{fo}^* ,

is a function of surface temperature, velocity, deposit structure and effective reactant concentration.

Previous Work

Hasson and co-workers (5) studied the initial deposition of calcium carbonate scale under conditions of constant heat flux. They found the deposition rate increased by 20% with a 20°F increase in surface temperature.

Knudsen and Storey (4) investigated the effect of surface temperature on the asymptotic fouling resistance for simulated cooling tower water. In contrast to Hasson's work, the asymptotic fouling resistance was found to be a strong function of temperature, changing by a factor of 20 with a surface temperature change of 60°F.

Watkinson, et al., (7) studied calcium carbonate scaling under conditions of constant wall temperature. The surface temperature decreases as scaling proceeds, thus making these data difficult to compare with those obtained at constant heat flux, where the surface temperature essentially remains constant.

Bott and Pinheiro (10) studied the velocity and temperature effects on Biological fouling. The slime thickness decreased with the increase in fluid velocity. It was found that temperature variation of only 5°C for two runs at the same Reynold's number

resulted in an increase of nearly 70% in the slime mass. The kinetics of bacteria growth is the key factor in determining the slime development.

Norrman and coworkers (12) studied the control of microbial fouling in circular tubes with chlorine. They found that the addition of chlorine caused partial film removal with a consequent increase in suspended particles.

RESEARCH OBJECTIVE

Previous work and theoretical aspects in fouling experiment have traditionally followed the build up of fouling at fixed operating conditions. A commercial operation can seldom be kept at fixed operating conditions for a long period of time. For example in a cooling water system, the velocity or temperature might change, or a leak might occur that could change the water quality.

Two examples as a result of change in operating conditions were reported by HTRI (8). In the first example, a fouling asymptotic was being approached when an acid leak occurred, changing the quality of water which gave a rapid increase in fouling resistance and a new secondary asymptote. The second example was as a result of a study to determine the high velocity flush out of the fouling deposits. The velocity was increased from approximately 3 ft/sec to 12 ft/sec. The fouling did indeed decrease considerably, all loose crystalline and sedimentary structure apparently being flushed out. The original velocity was restored and an extremely rapid build-up of fouling was observed. The new level of fouling which established itself in an asymptotic manner was actually higher than the original one.

The objective of this research was to experimentally study and analyze the effect of the velocity variation of cooling tower water, and to investigate the possibility of using high velocity flush-out as a method of controlling fouling. The experiments were started at

fixed operating conditions until an asymptotic form of fouling vs. time curve was obtained. Then the velocity was varied from a low velocity to high velocity in a cyclic manner.

Since fouling is a slow process the time required between these step changes in velocity was long enough to enable a good extrapolation of fouling vs. time curve. By changing the velocity in a cyclic manner, attempts were made to determine if fouling resistance levels off after a long period of time.

The result of the experiments gave insight into the extent to which velocity fluctuation effects fouling in industrial heat exchangers.

EXPERIMENTAL SYSTEM

The flow diagram of the experimental system is as shown in Figure 2. It essentially consisted of a test section, a storage tank, a centrifugal pump and a concentric tube heat exchanger.

The test section was an annular flow duct consisting of an outer transparent 1-inch I.D. acrylic tube (for visual observation) and a concentric 5/8-inch O.D. copper tube. The fluid flowed axially through the annular space between them. The copper tube had an electrically heated section of 6.5 inches, located about 12 inches from the fluid inlet.

A schematic cross section of the heated section is shown in Fig. 3. It consisted of a 9.9 inch long cartridge heater (0.495 inches, O.D., 240V 1000W), as shown in Figure 4. The lead wire from the electric heater was connected to a wattmeter and then to a 22V electric source.

The heat flux or the power input to the electric heater was varied (and easily held constant) by a power-stat and measured by a wattmeter.

Three copper constantan thermocouples were imbedded in the tube wall, as shown in Figure 5. It was important to install the wire in such a way that it would provide a minimum obstruction to the flow. The temperature measured by the thermocouples gave a

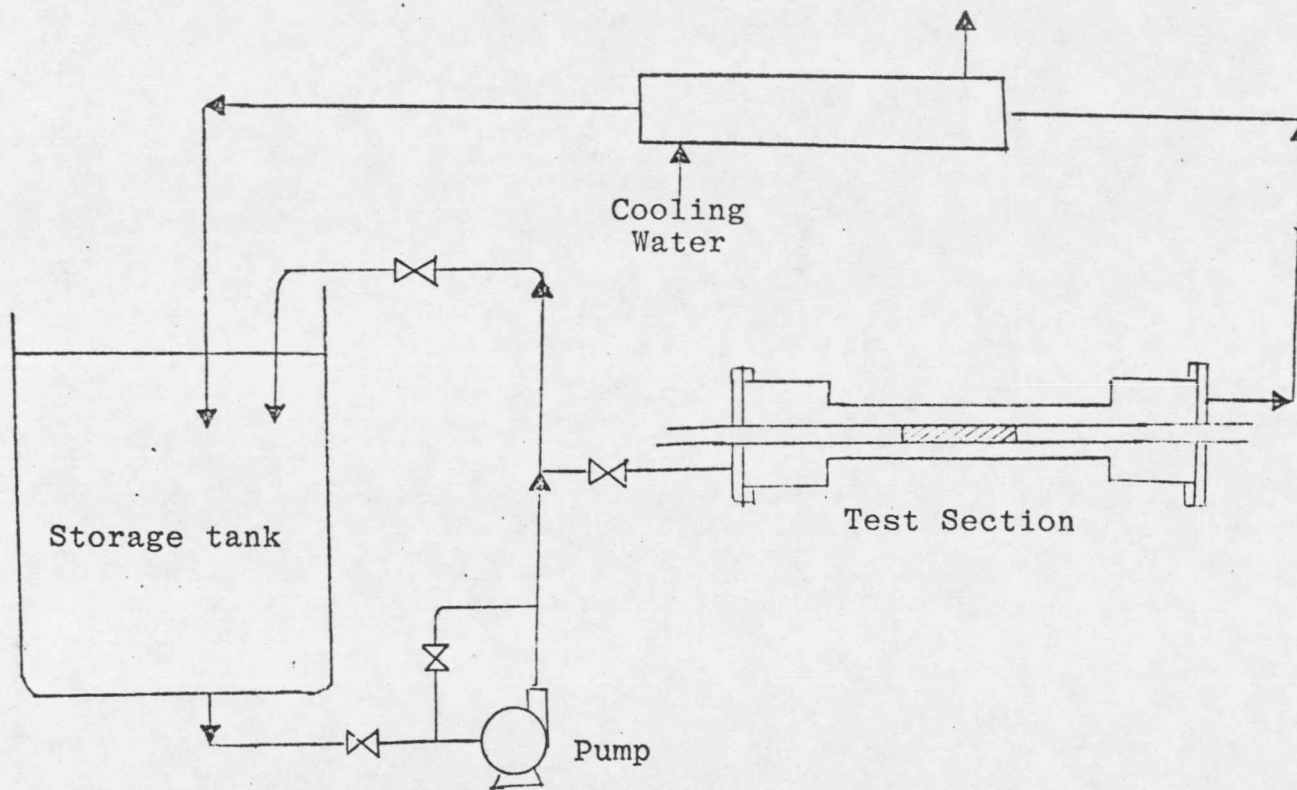


Figure 2. Simplified flow diagram of the process.

measure of local fouling at different points. Two of them were connected to a strip chart recorder for continuous data acquisition and the other was connected to a controller. The controller, which was installed for safety, was programmed to shut off the power input to the heater when the wall temperature went beyond a set point. This might have occurred, for example, if the pump had failed. The experiment had to be run continuously for many days and there was a real possibility that the belt used for driving the high speed pump might break.

The test section was connected to the rest of the system through a 1/2-inch copper tubing. The system was designed in such a way that the mass (and hence the velocity) of the water flowing through the test section could be easily controlled and varied by the use of a by-pass valve.

The water was pumped from the storage tank. Part of it flowed axially through the annular space in the test section and the rest was recycled through a by pass valve. Water was heated as it passes through the test section and was cooled in a concentric tube heat exchanger and returned to the system. The temperature of the fluid at the outlet and at the inlet of the test section was measured by a thermocouple in a thermal well.

The bulk temperature of the test fluid, its velocity and the

power input to the heater were held constant during the run. The level of the water in the storage tank was maintained at a constant level. Make-up water was added to account for loss by evaporation. Commercial bleach (chlorax) was added at the rate of 50 ml/day to suppress microbial growth. The bulk temperature was maintained constant at 35°C by controlling the temperature of the cooling water and the pH was kept between 8.1 and 8.5.

It is necessary to select a water composition typical of average cooling tower water. River water is the source of make up water for many industrial cooling towers. The composition of the cooling water from various industries was obtained and averaged to obtain a representative composition of cooling tower water make-up. Since fouling is a slow process, the concentration was increased to obtain a water which would scale relatively rapidly.

The major component of the cooling water were included, namely Ca^{++} , Mg^{++} , Na^+ , Cl^- , SO_4^{--} . Table 2 gives the amount of salts that were added to 165 liters of tap water to formulate the simulated cooling tower water (instead of distilled water) with the idea that the simulated water would have all the trace elements which are present in tap water.

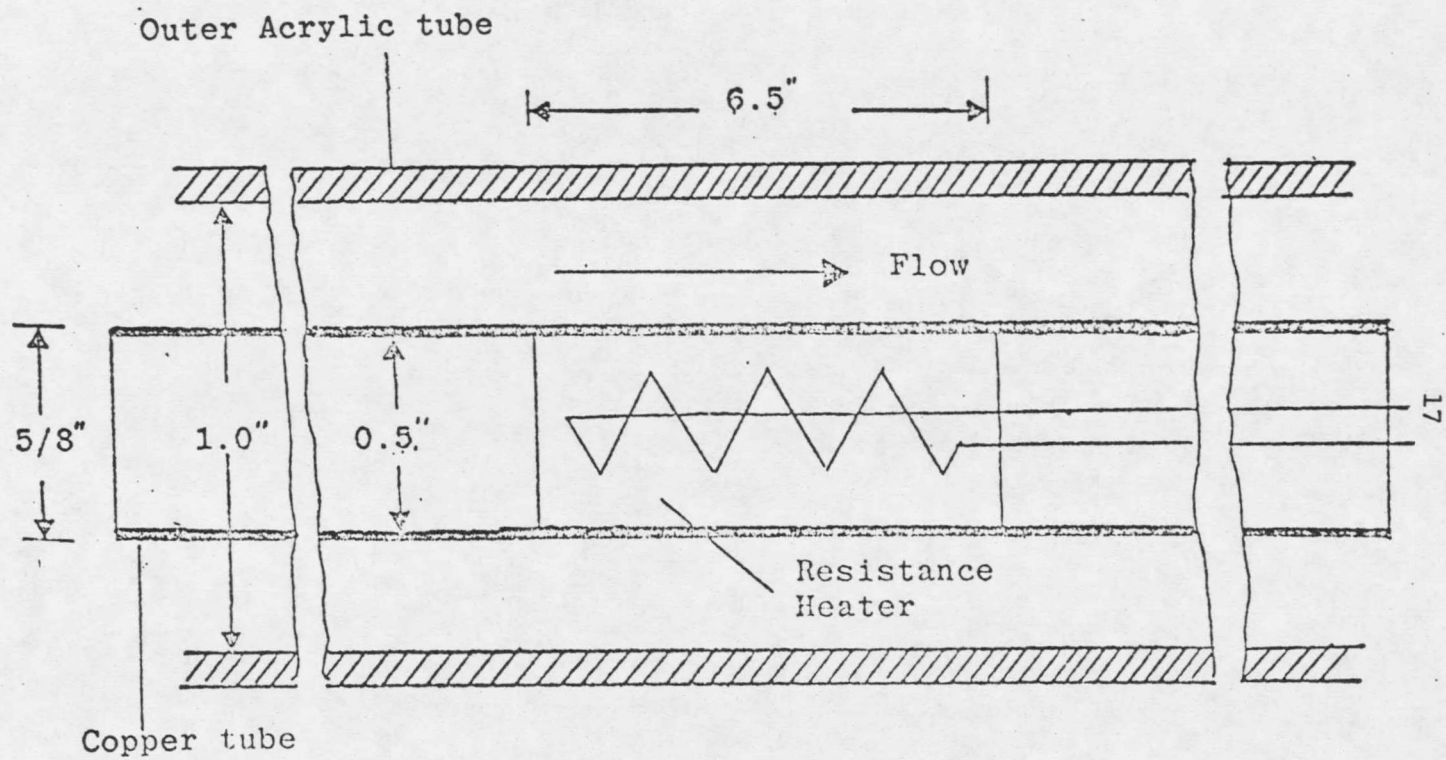
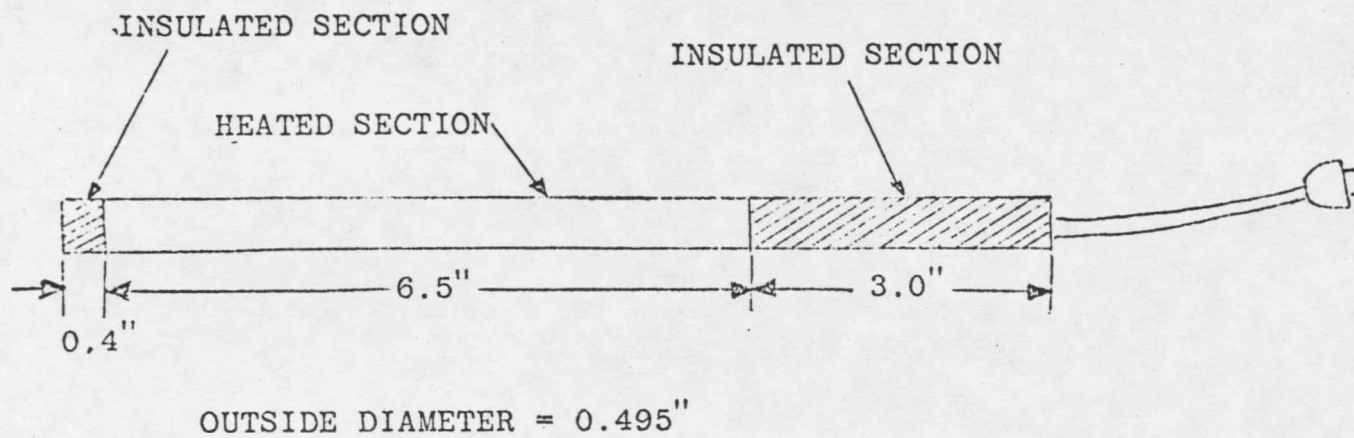


Figure 3. Cross section of test section.



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Figure 4. Details of electric heater.

Thermocouple Attachment Procedure.

1. Make small grooves in the section of the tube wall which is heated.
2. Place the junction of the thermocouple in the groove.
3. Solder the thermocouple in the groove.
4. File out the excess solder to make the tube surface smooth.

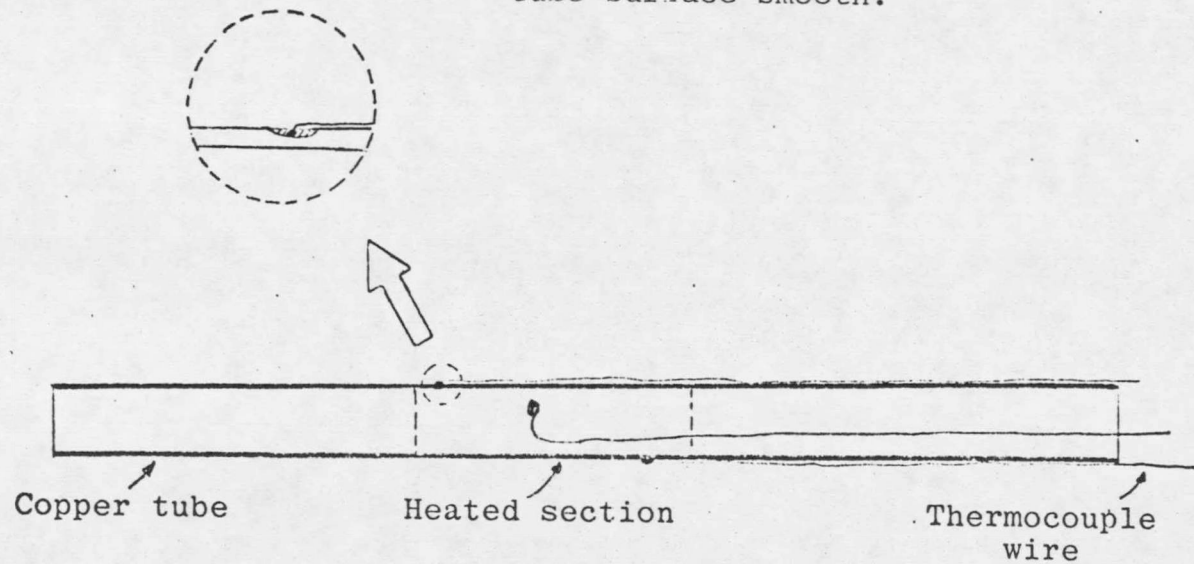
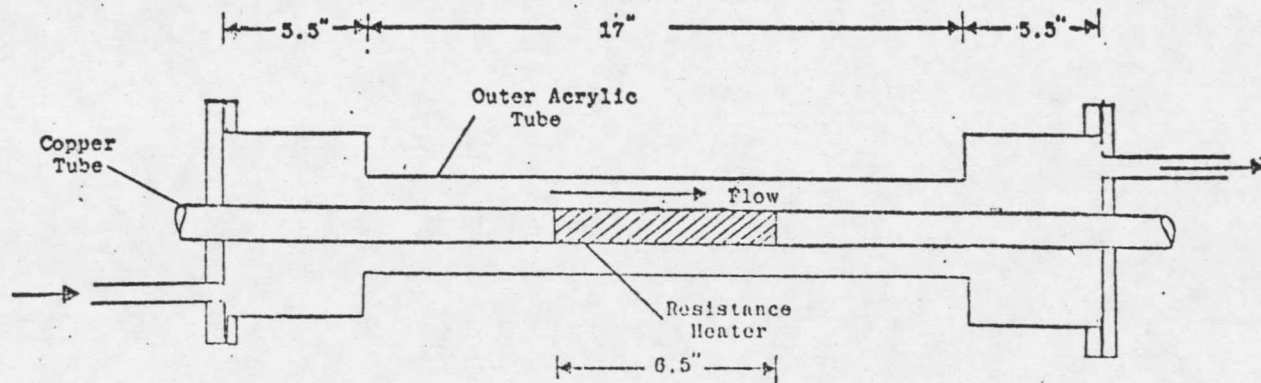


Figure 5. Thermocouple attachment method.



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Figure 6. Details of the test section.

EXPERIMENTAL PROCEDURE

For all runs, the experiment was started with a clean copper tube. The tube was "sand blasted" to make the surface rough, which in turn would foul the tube relatively rapidly. The bulk temperature was maintained at 35°C. The experiment was started with a bulk velocity of 2 ft/sec through the test section until an asymptotic form of fouling factor vs. time curve was obtained. At this point the velocity was increased from 2 ft/sec to 6 ft/sec for two hours and restored to the original velocity. The runs were made at a relatively low velocity (2 ft/sec) with the idea that it would enhance the fouling process, thereby shortening the length of the run. The heat flux or the power input to the heater was also maintained constant throughout the run.

Preparation of Simulated Water

To start a run it was necessary to prepare the simulated water. Table 2 shows the amount of chemicals added to 165 litre of tap water. Since calcium carbonate is insoluble in neutral water it was dissolved in a mixture of concentrated hydrochloric acid and nitric acid. One hundred and fifty grams of CaCO_3 was first weighed and dissolved in a minimum quantity of acid (generally excess calcium carbonate was added) to ensure that all acid was used or neutralized. The resulting solution was allowed to settle

Table 2. Water Preparation Summary.
(Chemicals added to 165 liters of tap water.)

Run	CaCO ₃ (gr)	Na ₂ SO ₄ (gr)	NaCl (gr)	MgSO ₄ (gr)	7H ₂ O (gr)	Na ₂ SiO ₃ (gr)	Mg(OH) ₂ (gr)	MgSO ₄ (gr)	NH ₄ H ₂ PO ₄ (gr/day)	C ₅ H ₉ O ₄ N (gr/day)
1	Tap Water									
2	83	150	25	250	50	154	-	-	-	-
3	80	100	20	250	-	-	-	-	-	-
4	100	150	20	250	-	-	-	-	-	-
5	90	150	20	250	-	-	-	-	-	-
6	110	150	20	250	-	-	-	-	-	-
7	100	200	20	250	-	-	-	-	-	-
8	100	250	20	250	-	-	-	-	-	-
9	88	250	50	250	-	-	-	-	-	-
10	133	250	50	300	-	-	-	-	-	-
11	98	250	50	300	-	-	-	-	-	-
12	110	250	50	-	-	-	-	150	0.222	-
13	110	250	50	-	-	-	-	150	0.222	8.25

and was decanted. The residual calcium carbonate was dried and weighed. The other chemicals were dissolved in water. The pH of the simulated was checked before starting the run and was kept between 8.1 and 8.5.

Assembling the Test Section

The surface of the copper tube was roughened by sand blasting the tube. Three grooves/cavities were made in the section of the tube which was heated. The junction of the thermocouple was placed inside the groove and soldered as shown in Figure 5. The thermocouple wires were placed along the tube and tied to the tube with thin wires.

Before inserting the heater into the tube, it was wrapped with aluminum tape/foil so that it would fit tightly inside the tube. It was then coated with a paste of copper antisieze compound. The test section was then assembled. The thermocouple wires were taken out through the two gaskets, which were placed between the flanges. The test section was then connected to the rest of the system.

The concentric tube heat exchanger in the system can be used for two different purposes: (1) During the start up it was used to raise the bulk temperature of the water to 35°C, and (2) During the normal course of the run it was used to cool the liquid coming out of the test section.

The by-pass valve was calibrated so that the water flow rate through the test section could be regulated. The power input to the heater was adjusted to give a wall temperature of at least 50°C. During the start up of a run, the wall temperature of the clean tube was determined at water velocities of 2 and 6 ft/sec.

The bulk temperature was controlled by controlling the temperature of the cooling water. The experiment was then continued until an asymptotic form of fouling resistance vs. time curve was obtained. During that time the water velocity, bulk temperature and heat flux were held constant.

The velocity was then increased from 2 ft/sec to 6 ft/sec through the test section for two hours and then restored to the original velocity.

RESULTS AND DISCUSSION

The experimental results are expressed in the form of fouling resistance, R_f , as a function of time (Appendix A). Thirteen runs were performed. All the experiments were operated at constant heat flux, constant bulk temperature, and constant water using simulated cooling tower water. Table 2 shows the amount of cooling various chemicals added to 165 litres of tap water. All the experiments were started with a clean tube with zero resistance at outset and continued till an asymptotic form of fouling resistance vs. time curve is obtained. If the fouling resistance as measured by the increase in wall temperature became too high, the preset high temperature controller (85°C) was programmed to shut down the heater. Such premature shutdowns occurred in Run 2 and Run 9.

No commercial bleach (chlorax) was added in Runs 1 through 7. Fifty ml/day of chlorax was added in Run 8, Run 9, Run 10, and Run 11. Twenty five ml/day of chlorax was added in Run 12. Run 13 was performed to study the effect of microorganisms on the fouling resistance of heat transfer surfaces. In general, these experiments can be divided into three groups based on different objectives.

Group 1

These experiments were done to study the effect of water velocity on asymptotic fouling resistance. Two different water

velocities were used: 2 ft/sec and 6 ft/sec. Run 1 was carried out using tap water at a velocity of 2 ft/sec through the test section for a period of five days. No deposition or fouling was observed. This might be due to the very low calcium content of tap water. An increase in wall temperature of 3°C was observed during this period. Run 2 was the first run performed using simulated cooling water. This run was stopped after six hours, as sodium silicate precipitate was deposited rapidly on the tube. During this period an increase in wall temperature of 20°C was observed.

Run 9 was carried out at 2 ft/sec and Run 11 at 6 ft/sec. On comparing the results (Fig. 12, Fig. 14), it can be seen that the fouling resistance decreased with an increase in water velocity. In other words, as the velocity increases the shear force at the wall increases. Therefore, the fouling resistance decreases, or it will take more time to foul. This was clearly seen while making visual observations. At a water velocity of 2 ft/sec the deposit on the heated section of the tube was visible in two or three days, while at 6 ft/sec it took more than six days to foul.

In Run 9 a rapid increase in wall temperature (and hence the fouling resistance) was observed after 150 hours because of suspended particles in the system. Run 6, Run 7, and Run 8 have identical water quality except for the amount of Na_2SO_4 and shows

different rate of fouling; these results cannot be used to compare the rate of fouling and/or asymptotic fouling resistance (at the same velocity and identical water quality), mainly for two reasons:

- (1) The roughness of the clean tube may vary
- (2) The thermocouple measures the local rate of fouling at a particular point. The local rate may not be the same.

Group 2

In this set of experiments attempts were made to study the possibility of using high velocity flush out as a method of controlling fouling. All the experiments were started with a clean tube and continued until an asymptotic form of fouling resistance vs. time curve was obtained. During that period it was operated at a constant velocity of 2 ft/sec.

The velocity of the water through the test section was increased to a higher velocity for two hours keeping bulk temperature and heat flux constant. It was then restored to the original velocity. This was continued in a cyclic manner. Two different higher velocities, 4 ft/sec and 6 ft/sec, were used.

In Run 3 (Fig. 7), the velocity was increased to 4 ft/sec through the test section for two hours. As the velocity was increased the wall temperature (and hence the fouling resistance) decreased and remained the same for two hours. On restoring the velocity to the original value the same fouling resistance was

observed. Since the fouling resistance before and after remained the same, a velocity of 6 ft/sec was used in the rest of the run.

In Run 5, Run 7 and Run 8 the velocity was increased to 6 ft/sec for two hours. In this case also, for all successive flush-outs, the fouling resistance before and after the flush out remained the same. The fouling resistance increased for the period between the two flush outs, where it was operated at 2 ft/sec.

In Run 10, instead of increasing the velocity for only two hours, it was increased and continued at 6 ft/sec for the rest of the run (Fig. 13). Even running at 6 ft/sec continuously, an increase in fouling resistance with time was observed.

Flush out at velocities greater than 6 ft/sec were not carried out because of the limited capacity of the pump.

Group 3

Two runs were made to study the effect of the deposition and growth of micro-organisms on heat exchanger surface. To meet this objective, two identical runs were made, one without microorganisms and the other with microorganisms. The water quality, water velocity, bulk temperature, and heat flux were kept same in both runs.

Run 12 was carried out at 2 ft/sec by adding 25 ml/day of chlorax to suppress the microbial activity. This run was stopped after 185 hours.

In Run 13, the system was inoculated with sewage seed (bacteria). Fifty mg/l/day of Glutamic acid (substrate) was added to the system. The carbon to nitrogen ratio was kept at 5:1. Phosphorus was added in the form of Ammonium phosphate. Both the runs were carried out for the same period of time. A rapid increase in fouling (Fig. 15) was observed in the first twenty hours.

The final value of fouling resistance was almost twice the value obtained in Run 12 (without microorganisms).

CONCLUSION

Within the range of operating conditions and water quality reported herein, it is concluded that:

- 1) It is not possible to use a velocity of 6 ft/sec or less to flush out the deposit as a method of controlling fouling in a system which is treated with 'bleach' so that there is no biological growth in the system. This result cannot be applied to a system where microbial fouling is occurring simultaneously with crystallization and sedimentation.
- 2) The fouling resistance was found to decrease as flow velocity increases.
- 3) The presence of microorganisms in the system increases the rate of fouling and gives a higher asymptotic fouling resistance, as compared to an identical system without microorganisms. This conclusion is based on one test run and needs further study.

RECOMMENDATION FOR FUTURE RESEARCH

The biological fouling of heat transfer surface is an important problem in industry and is probably one of the major constraints in terms of cooling water efficiency in many processes. With the increasing use of biological material in industry, the problem of biofilm growth on heat transfer surface and process surface will become increasingly important. The presence of biofilms on both sides of the heat exchanger will further impair heat transfer efficiency due to added resistance.

Therefore, a complete understanding of the mechanism of biofouling in systems where microbial fouling occurs simultaneously with crystallization and sedimentation is necessary. The important factors which should be taken into account are the engineering effect (heat transfer efficiency, pressure drop, film thickness, and energy losses), the microenvironment of the organism in the film, and the factors affecting the organisms (pH, temperature, dissolved oxygen, and nutrient concentrations, to name a few).

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NOMENCLATURE

A = heat transfer surface area sq. ft.

h = film coefficient BTU/hr. sq. ft. °F

q = heat duty, BTU/hr.

R_f = fouling resistance of sq ft Hr/BTU

R_w = resistance offered by wall of sq ft Hr/BTU

U = overall heat transfer coefficient BTU/hr sq ft °F

U_i = overall heat transfer coefficient of the initially clean surface BTU/hr sq ft °F

T_w = wall temperature °F

T = temperature °F

Subscripts

i = inside of tube

o = outside of tube

f = fouled condition

c = clean condition

b = bulk condition

s = surface condition

APPENDIX A

Fouling Resistance Time Curves

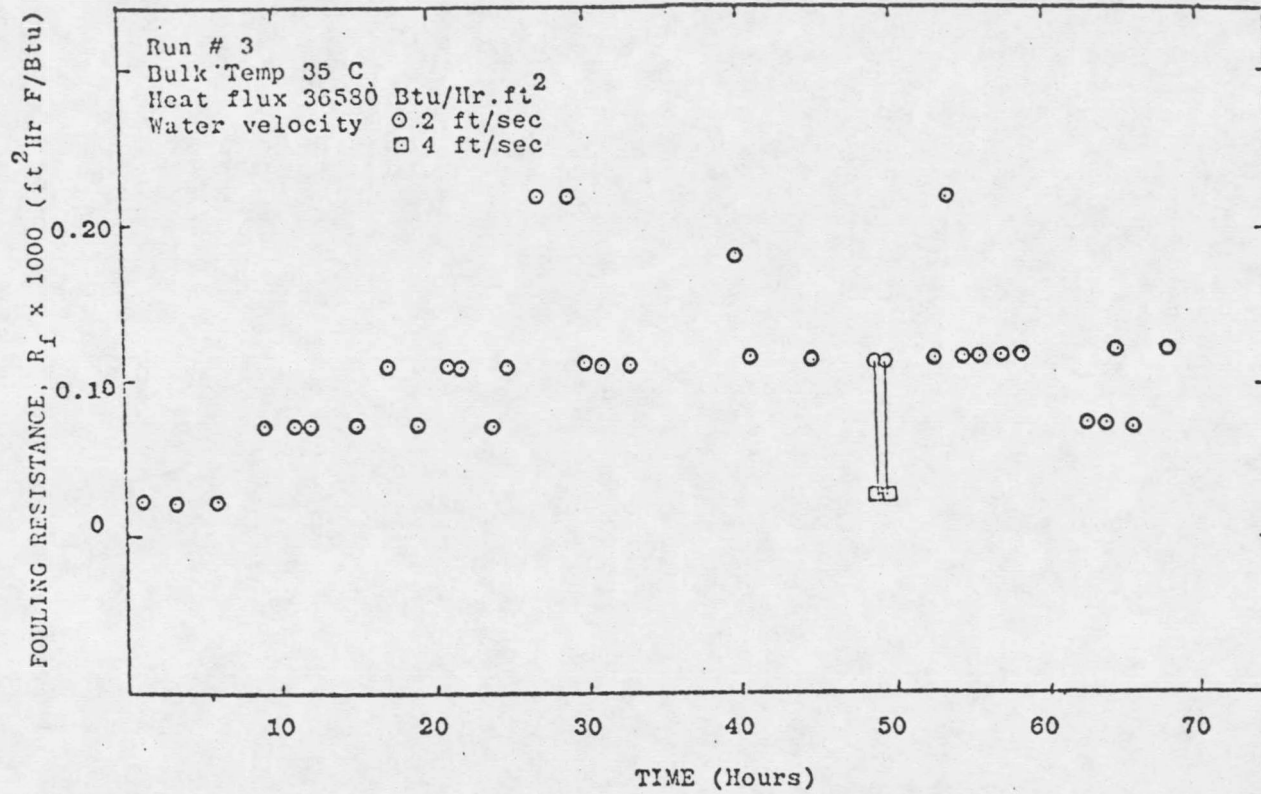


Figure 7. Fouling Resistance vs.time - Run 3

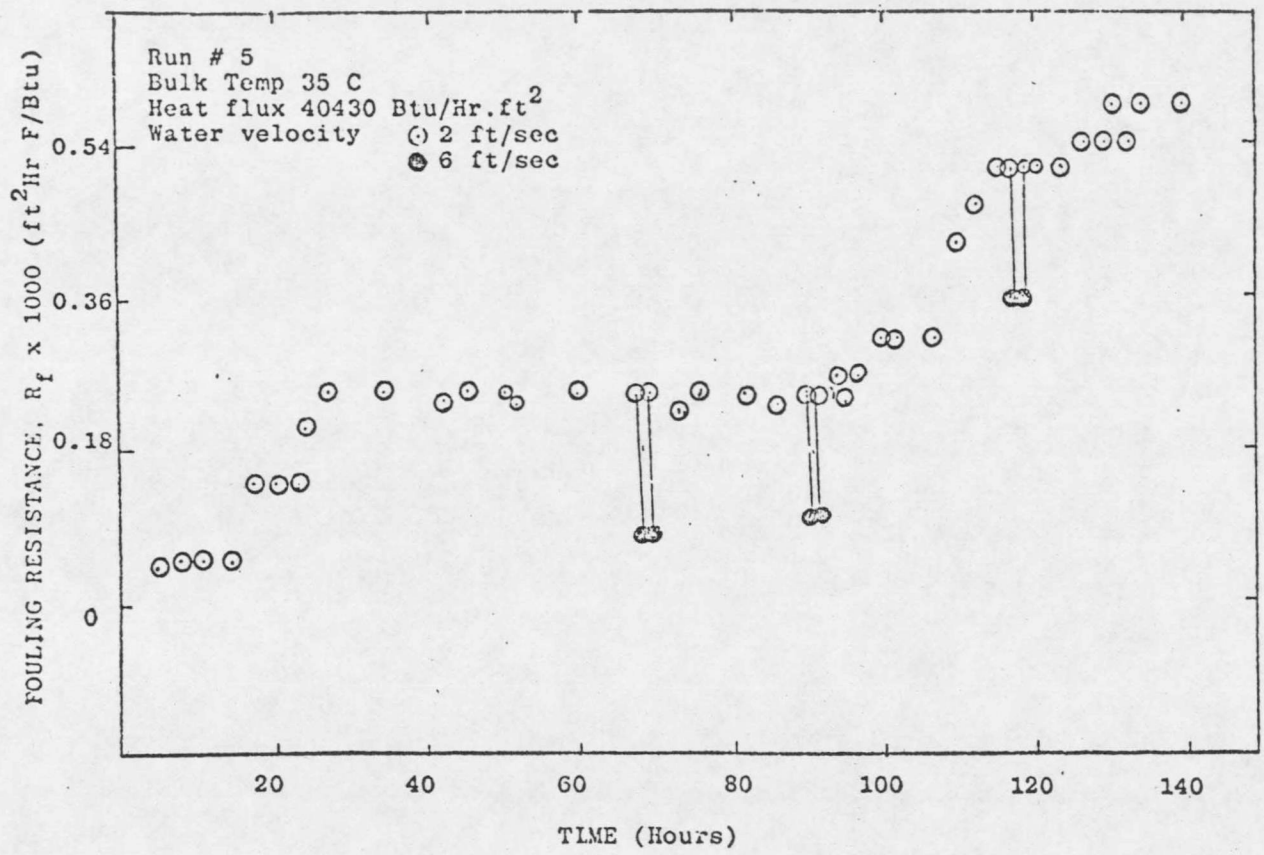


Figure 8. Fouling Resistance vs. time - Run 5

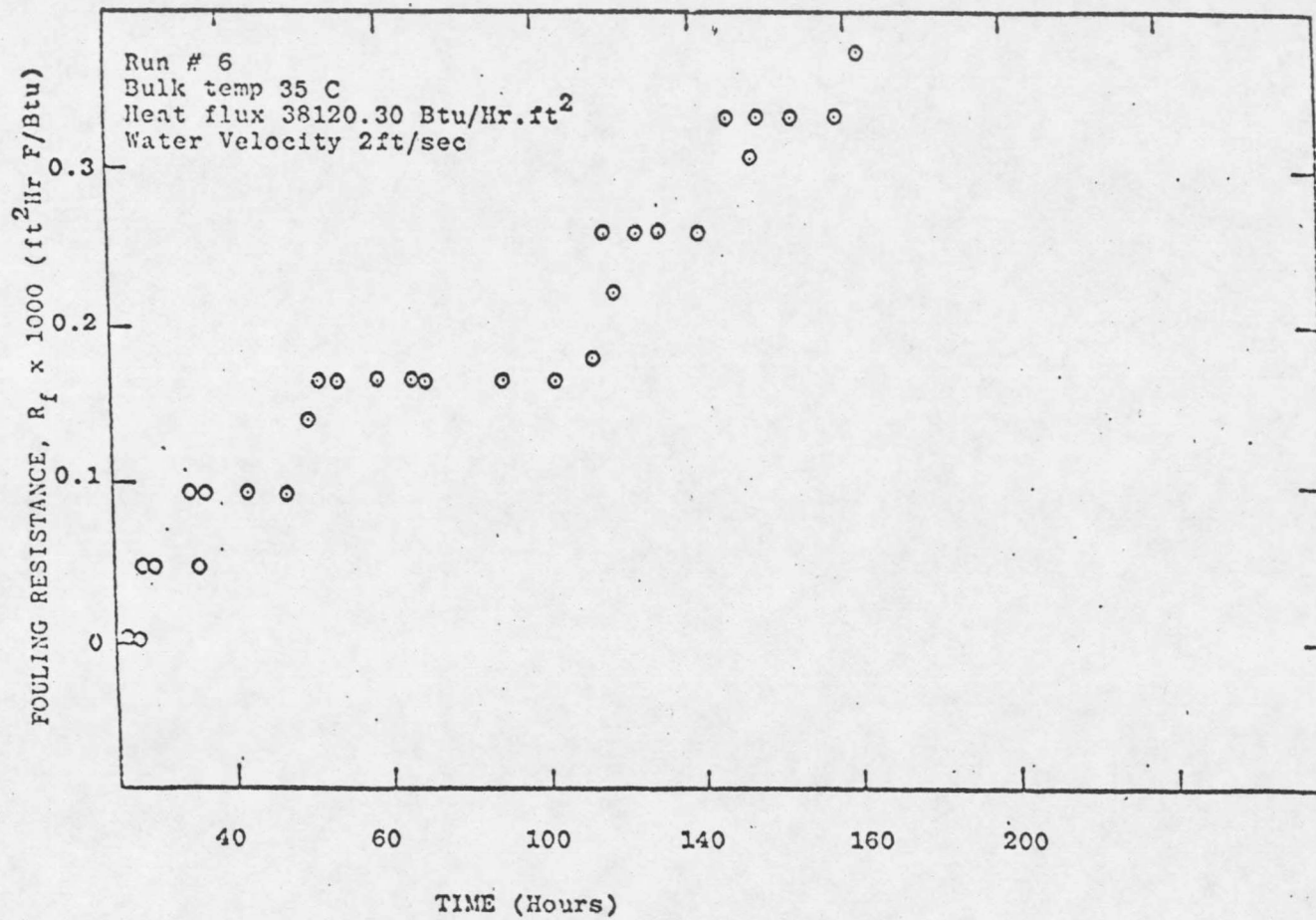


Figure 9. Fouling Resistance vs. time - Run 6

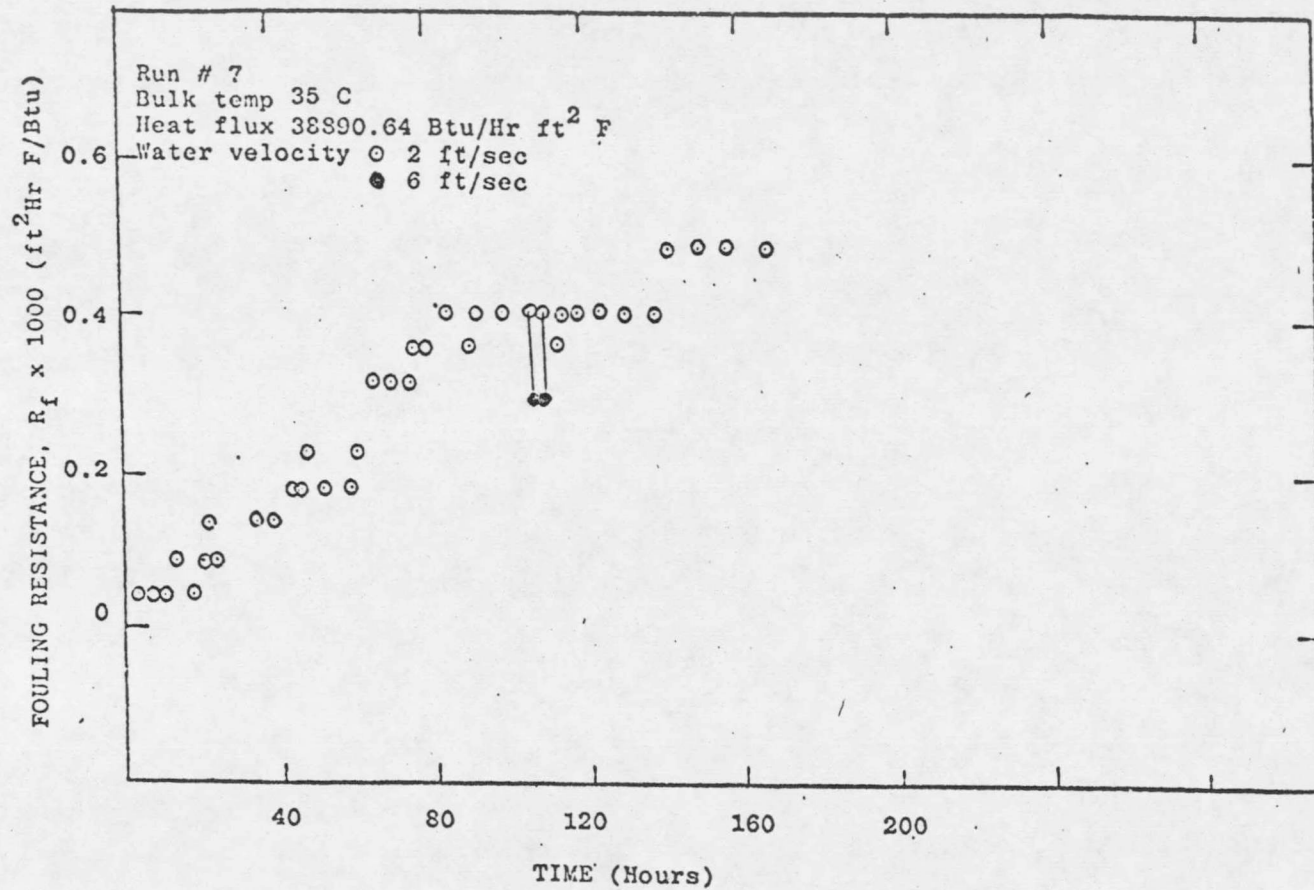


Figure 10. Fouling Resistance vs.time - Run 7

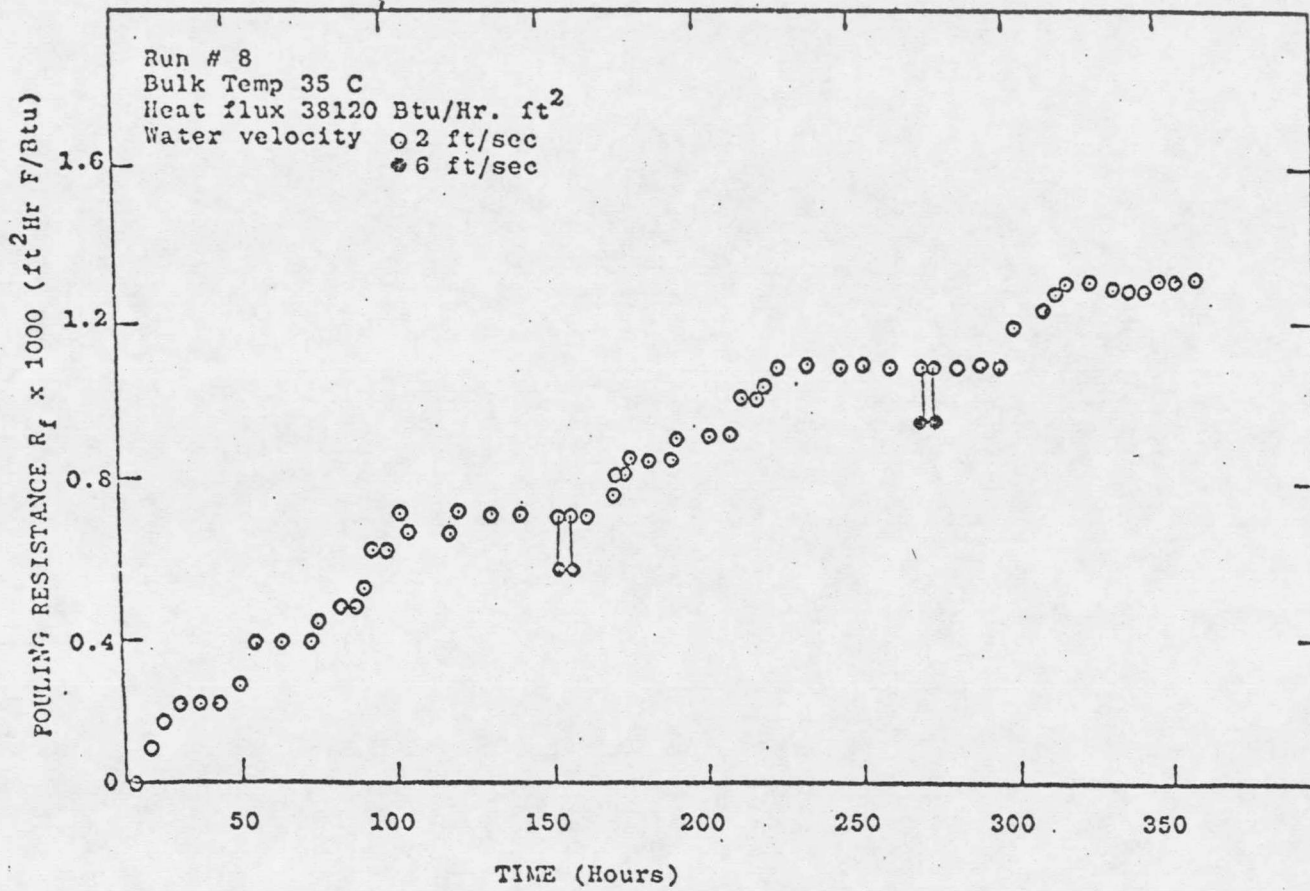


Figure 11. Fouling Resistance vs time - Run 8

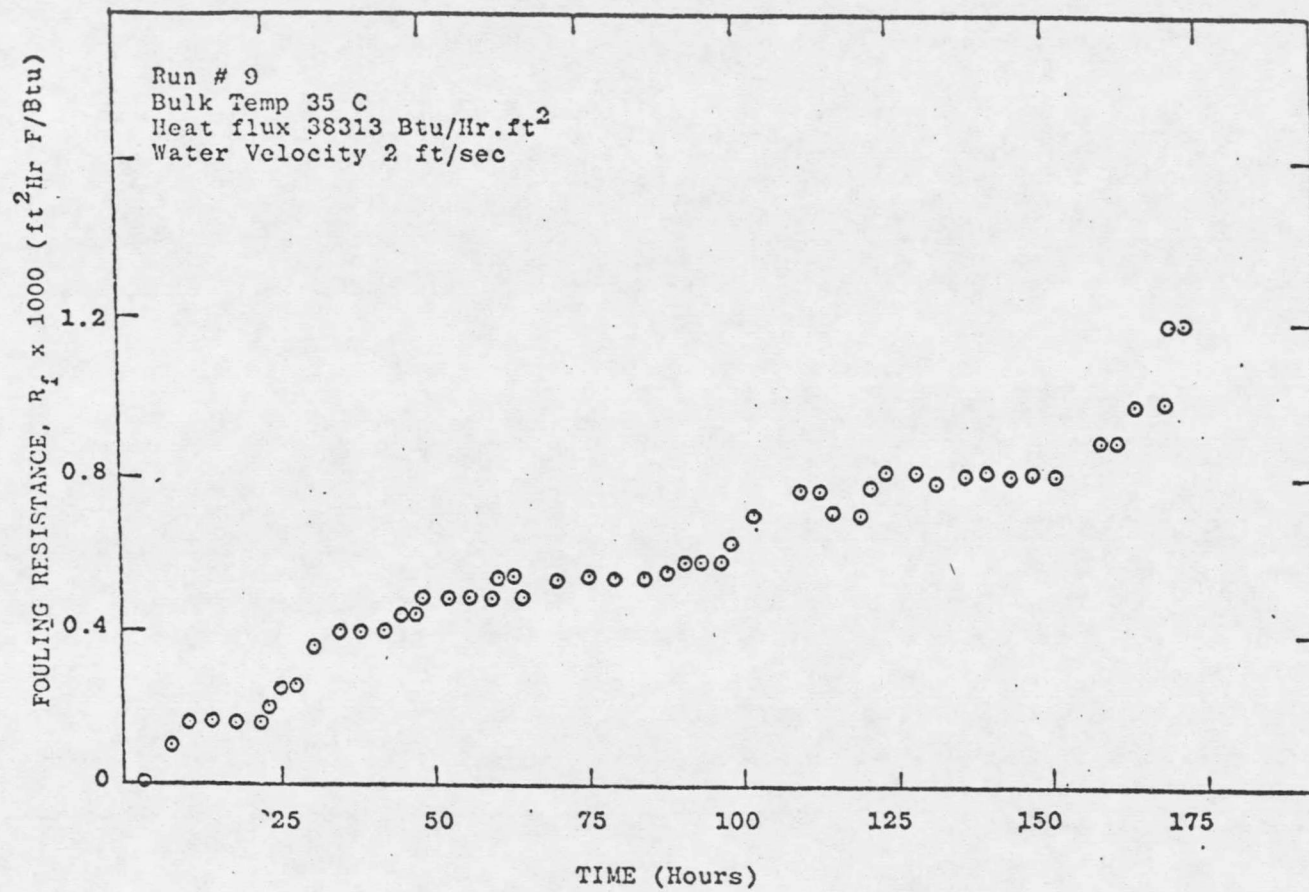


Figure 12. Fouling Resistance vs.time - Run 9

