EFFECT OF SURFACE TEMPERATURE ON PARTICULATE AND CRYSTALLIZATION FOULING

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ABSTRACT

The aim of the present experimental work is to study the influence of surface temperature on both particulate fouling (PF) and crystallization fouling (CF) of heat transfer surfaces. For this target, an experimental setup, with a Perspex transparent test tube of 200 cm length and 5.92 cm inner diameter has been designated and constructed. Water with a concentration of 1g/lit in case of PF and 42 g/lit in case of CF is used as a test fluid. The experimental runs have been carried out under different surface temperatures of 70, 88 and 103^{o}C (for PF) and 62, 84 and 106^{o}C (for CF). The experimental run is carried out for a long enough time to reach the asymptotic fouling resistance (in PF) and the maximum allowable working time of the heating coils (in CF). Obtained results show that the surface temperature has a great effect on the fouling resistance in both the fouling modes. In case of PF, both the fouling resistance and the asymptotic fouling resistance decrease with increasing the surface temperature, where in the case of CF, the fouling resistance increases in the same sense. The saw tooth effect is observed only in the PF fouling mode. In all the experimental tests, the delay time is very small and seems to approach zero. This may be due to high concentration of test fluids.

Keywords: Surface temperature, particulate, crystalline, fouling, heat transfer.

NOMENCLATURE

A	Heat transfer area, m^2
C_p	Specific heat of circulating water, *kW/kg.* ^oC
L	Heaters length, *35, 45, 65 cm* (in PF) and *35, 4o, 65 cm* (in CF)
$\dot{m}$	Water mass flow rate, *kg/s*
R_f	Fouling resistance, $m^2.^oC/kW$
U	Overall heat transfer coefficient, $kW/m^2.^oC$
U_f	Overall heat transfer coefficient for fouled condition, $kW/m^2.^oC$
U_c	Overall heat transfer coefficient for clean condition, $kW/m^2.^oC$
Q	Heat transfer rate, *kW*
t	Time, *hr*
t_c	Time constant, *hr*
T_i	Test fluid inlet temperature, ^oC
T_o	Test fluid outlet temperature, ^oC
T_s	Surface temperature, ^oC

Greek letters

β = $1/t_c$

$\Delta\theta_m$ Logarithmic mean temperature difference, °C

Abbreviations

PF Particulate fouling
CF crystallization fouling

INTRODUCTION

Fouling of heat transfer surfaces is a major reason for increasing energy consumption, maintenance and operational costs in heat exchangers. Reduction in flow area due to fouling causes an increase in pressure drop across the apparatus [1-8]. Based on the different physical and chemical processes involved, the fouling can be classified as; crystallization, particulate, chemical, corrosion, solidification and bio-fouling. The fouling process is indicated by the fouling resistance, R_f which can be measured experimentally, either by a test section or from the decreased capacity of an operating apparatus [2-4]. The fouling results are presented by the fouling curve, which indicates the relation between the fouling resistance, R_f and the time. The most common fouling curves are the linear mode, the asymptotic mode and the falling rate mode curve as shown in Fig. 1. The delay time, t_d indicates an initial period before fouling occurs.

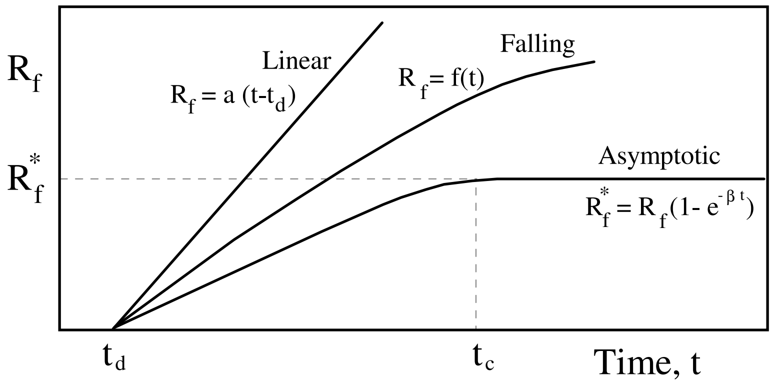

Fig. 1. Fouling curves.

The fouling of a heat transfer surface in contact with fluid depends mainly on the characteristics of the fouling fluid, flow velocity, surface temperature, fluid bulk temperature, material and geometry of the heat transfer surface. Many investigators have studied the fouling phenomenon theoretically and experimentally. Kern and Seaton [1] have cited the first and pioneer mathematical model for the fouling. They stated that the fouling rate could be estimated as the difference between the deposition and removal rates. Watkinson [5] reported experimentally the effect of fluid velocity on the asymptotic fouling resistance for three different operating foulants and obtained a correlation for each.

Epstein, 1988, proposed a simple model to describe the asymptotic fouling type. He assumed that the deposition rate is constant, where the removal rate is proportional to the thickness of the deposited layer. Li and Webb [17] studied the effect of different fouling types on the fouling resistance. A comparison between pure particulate fouling and combined precipitation and particulate fouling had been done. They found that, the fouling resistance due to pure particulate fouling is less than that due to the combined fouling. Kim, *et al* [18], investigated the effect of electronic anti-fouling (EAF) technology on fouling mitigation in an open cooling tower systems. They found that, at the end of 270-hour tests, the fouling resistance with EAF treatment was about 70% less than that without EAF treatment, at the end of 270 hour tests.

The effect of surface temperature on the surface fouling has been studied by several researchers [2,3,8,10]. In general, there results indicated that the effect of surface temperature on fouling rate is not well defined. Increasing the surface temperature may increase, decrease or has no effect on the fouling rate. On the light of the previous review and brief discussion shown above, the effect of surface temperature on fouling was not completely considered neither theoretically nor experimentally. Therefore, the present work deals with the effect of surface temperature on both particulate and crystallization fouling.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is designed to measure the fouling resistances at constant flow velocity and different surface temperatures. Therefore, three electric heaters with the same diameter (1.2 cm) and different power are fixed in the test tube centerline as shown in Fig. 2. Each heater is subjected to the same flow velocity (0.008 m/s), foulant concentration and material. The test tube (200 cm length and 5.92 cm inner diameter) was made from transparent Perspex for visual observation. As shown in the figure, a 100 liters storage tank is used to cool the circulating test fluid. This tank is provided with a stirrer to give a homogeneous test fluid and to prevent the precipitation of foulant outside the test section. The circulating pump extracts water from the tank to the test tube. After passing through it, the water returns back to the tank where it is cooled to the same original temperature before entering the test tube again. City water in an open circuit is used for cooling the test fluid in the tank.

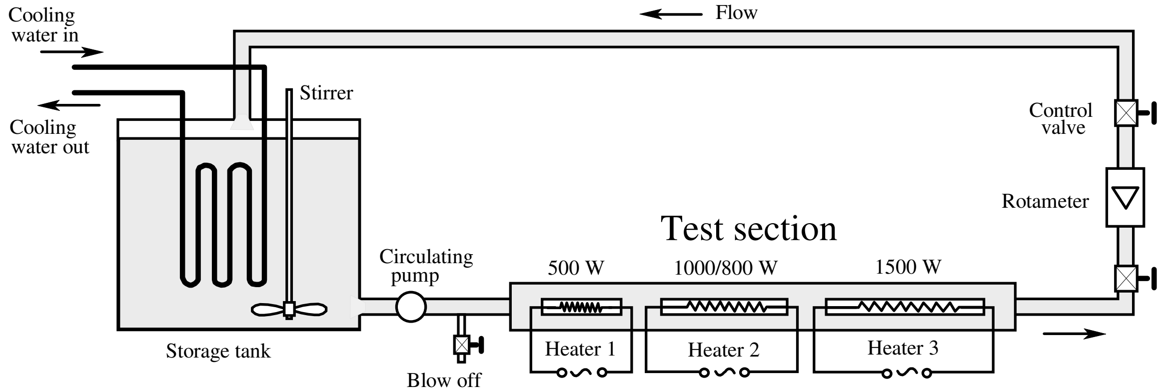

Fig. 2. Layout of the experimental setup.

Manual valves are used to control the flow rate, which is measured by the aid of calibrated rotameter. The test section is suitably instrumented to measure the mean surface temperature of each heater, the bulk water temperature before and after each heater and the tank water temperature. These temperatures are measured by means of thermocouples and recorded with a multi-point temperature recorder that is a self-balancing, automatic and manual switching, with a sensitivity of 0.01°C. The locations of the thermocouples are selected based on the previous experimental work of investigators.

The tank is facilitated with a low speed stirrer to maintain uniform fouling material in the test fluid before entering the test tube. Since the flow rate of test fluid entering the tank is equal to that leaving; the water level in the tank remains unchanged. This experimental setup is constructed in the Hydraulic Machines Laboratory, Faculty of Engineering, Mansoura University, Egypt.

The experimental study consists of two runs. The first run (I) is concerned with the particulate fouling and it is performed along 270 hrs of operation over 9 months and equipped with (500, 1000 and 1500W) electric heaters. The second run (II) is concerned with the crystallization fouling and it is performed along 30 hrs over 5 months and equipped with new electric heaters (500, 800 and 1500W). The system is subjected to preliminary tests to ensure proper operation and chick any leakage from its components. Each run is started by pumping water from the tank to flow over the three heaters in the test section to allow heat exchange between them and test fluid. The flow of the test fluid is controlled by manual valves to keep constant flow velocity at 0.008 m/s in all runs. Then, the test fluid leaves the test tube to the rotameter where its flow rate is measured.

In case of PF, the concentration of solid particles is adjusted and measured by a turbidity meter (model 2100 A). Make up solid particles or pure water is added to the storage tank to keep a constant concentration. To prepare the solid particles in a suitable size for the colloidal solution, a suitable quantity of alluvium has superheated in an oven for 24 hrs, then grannies in a mixer and bolted by bolters of size 70 μm. Then it is tested and calibrated in the chemical laboratory. To insure the colloidal solution, filtration papers that give a maximum particle size of 45 μm are also used. Preliminary tests have shown that the best concentration to keep the solid particles in a colloidal solution is 1 gm/lit. On the other hand, seawater from the Red sea, Sharm El-Sheikh, Egypt with a concentration of 42 gm/lit (42000 ppm) is used in case of CF experimental tests.

GOVERNING EQUATIONS

To calculate the fouling resistance, R_f a computer program is prepared using the measured bulk water temperature before and after each heater in the test section, the surface temperatures of the three heaters and the water mass flow rate. The value of R_f is determined by subtracting the fouling resistance when the test section is clean (at time zero) from that when it is fouled as,

$$R_f = \frac{1}{U_f} - \frac{1}{U_c} \tag{1}$$

Where, U_c and U_f are the overall heat transfer coefficients for clean and fouling conditions respectively. These coefficients are obtained from the general heat transfer equation $Q = U\,A\,\Delta\theta_m$ as,

$$U_c = \left(\frac{Q}{A\,\Delta\theta_m}\right)_c \qquad \& \qquad U_f = \left(\frac{Q}{A\,\Delta\theta_m}\right)_f \tag{2}$$

Where, Q is the rate of heat transfer that can be also obtained from:

$$Q = \dot{m}\,C_p\,(T_o - T_i) \tag{3}$$

and, $\Delta\theta_m$ is the logarithmic mean temperature difference,

$$\Delta\theta_m = \frac{(T_s - T_i) - (T_s - T_o)}{Ln\left((T_s - T_i)/(T_s - T_o)\right)} \tag{4}$$

Asymptotic type of fouling can be described by an exponential equation as,

$$R = R_f^{*}\,(1 - e^{-\beta t}) \tag{5}$$

Where, R_f^{*} is the asymptotic fouling resistance, ($m^2.^oC/kW$)

β = $1/t_c$ where t_c is the time constant, hr.

RESULTS AND DISCUSSIONS

As mentioned before, the experiments are divided into two runs (I and II) at different surface temperatures. In run (I), the PF is tested at surface temperatures of 70, 88 and 103^{o}C where in the second run (II), the CF is tested at surface temperatures of 62, 84 and 106^{o}C. In order to monitor an approximate value of the asymptotic fouling resistance in PF in run (I), the experiment takes 270 hours net working time and terminated when the fouling resistance approached an asymptotic value. In run (II), the operating time was terminated at 30 hours because the heaters are burnt out after this period due to the high fouling resistance.

The experimental results of PF run (I) represent graphically the fouling resistance, R_f as a function of time. Figures (3, 4 and 5) show the variation of R_f with time for surface temperatures of 70, 88 and 103^{o}C respectively. The broken line connecting the points to show the "saw teeth" effect nature of the fouling, which is observed in all the PF experimental runs. This effect is a result of partial removal of some deposits due to "sapling" or "sloughing" followed by a rapid buildup of deposits. In the last 50 hours, the fouling resistance appears to be approximately constant and the asymptotic fouling resistance, R_f^{*} is almost attained. The average curve of the measured data is plotted by a smooth line in all figures in order to show the trend of fouling.

The fouling resistance appears to be small during the initial period. Negative values of R_f in the early stages are even observed. As fouling layer starts to build up, it causes the surface to be roughening, and subsequently the local heat transfer coefficient increases. Therefore, the calculated fouling resistance may appear to be negative in this stage. As the fouling layer thickness increases, its thermal resistance increases due to the lower thermal conductivity of the fouling material. This effect opposes the improvement of the local heat transfer coefficient due to the surface roughness and the fouling positive values appeared.

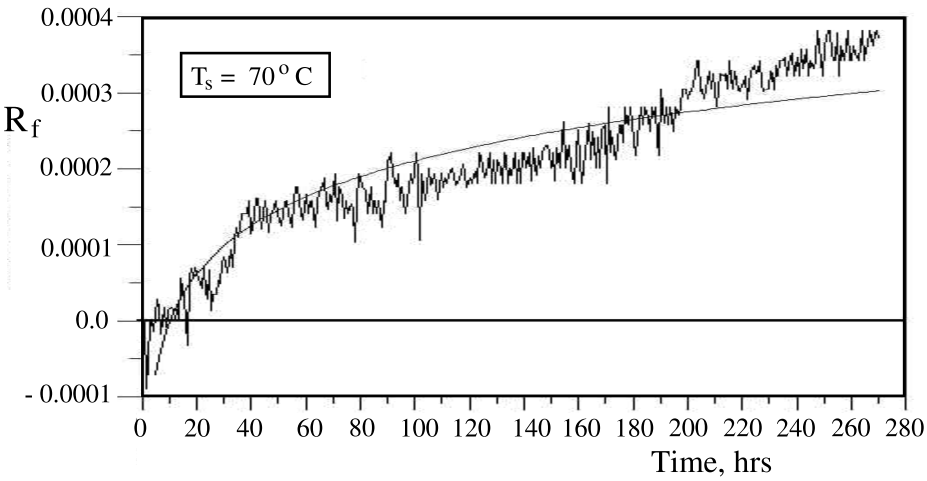

Fig. 3. Particulate fouling curve for $T_s = 70^o$ C.

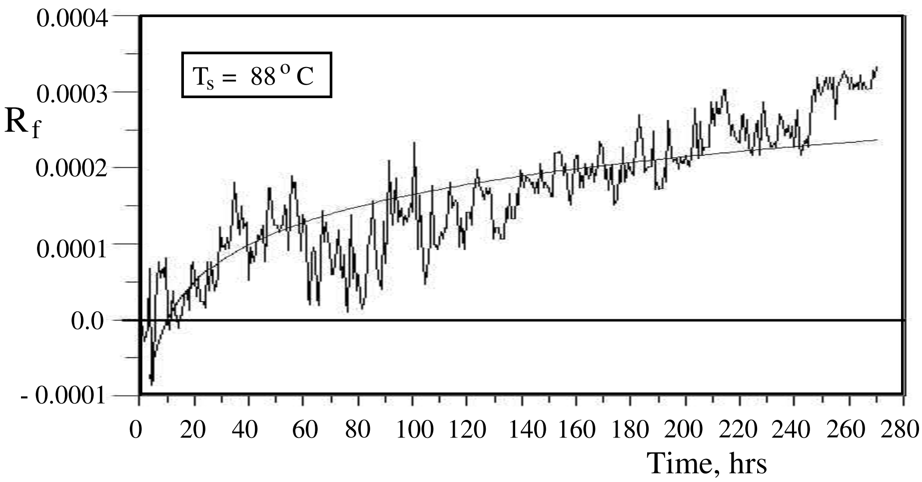

Fig. 4. Particulate fouling curve for $T_s = 88^o$ C.

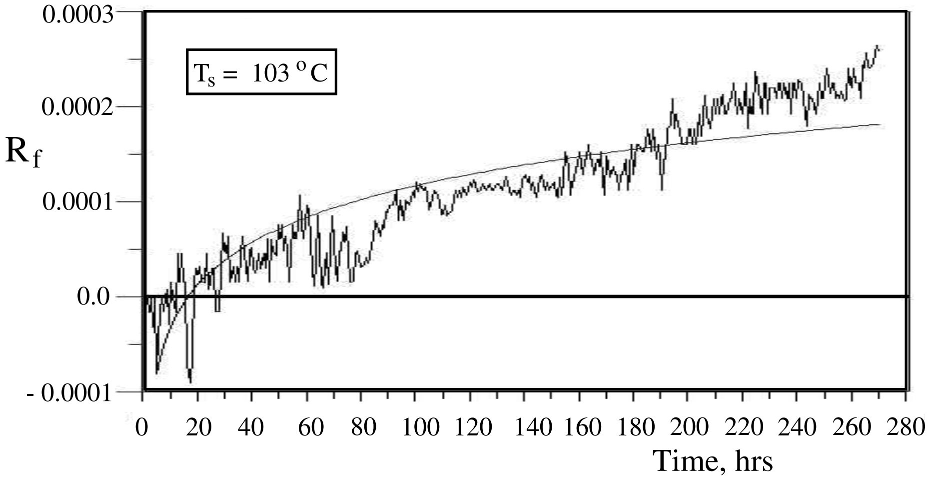

Fig. 5. Particulate fouling curve for T_s = 103° C.

The fouling curves for the three surface temperatures are plotted together in Fig. 6 in order to compare between them. From Figures 3, 4, 5 and 6, it can be seen that:

- The obtained fouling resistance in PF case is of the asymptotic type.
- The saw tooth effect is observed in all curves.
- The delay time is almost zero.
- At the beginning of operation, some improvement in overall heat transfer coefficient is observed and negative values of fouling resistance are attained. This is due to the roughening of heat transfer surface because of odd distribution of deposits on it.
- The fouling and asymptotic resistances decrease by increasing surface temperature.

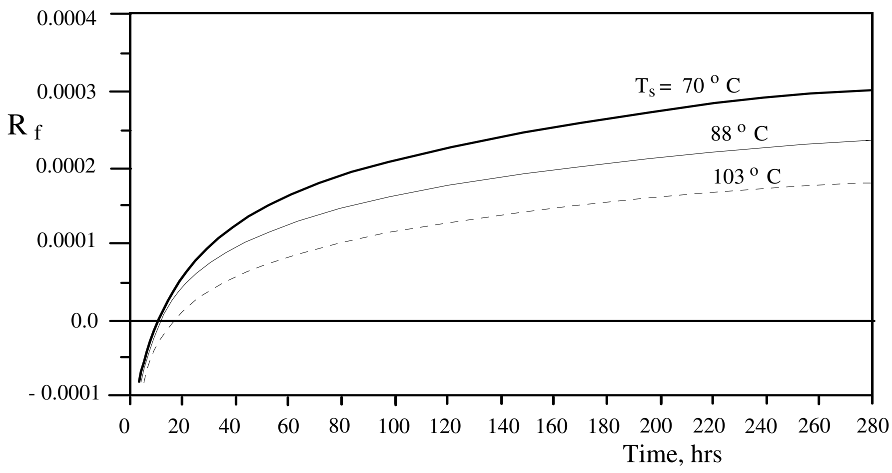

Fig. 6. Particulate fouling curves for different T_s values.

Referring to equation (5), the values of R_f^*, t_c and β at different values of T_s are given in Table 1. The corresponding overall heat transfer coefficient, U_c is also given.

Table 1. Summary of PF results

T_s , °C	U_C , (W/m^{2o}C)	R_f^* , (m^2.°C/W)	T_c , hr	$\beta = 1/t_c$, (hr^{-1})
70	2840.06	0.0003	83	0.012
88	2223.8	0.00024	88	0.0113
103	2185.26	0.00018	92	0.0108

Figure 7 shows the variation of asymptotic fouling resistance, R_f^* with the surface temperature, T_s. It can be seen that R_f^* decreases as T_s increases according to the best fit curve shown in Fig. 7. The relation can be expressed as,

$$R_f^* = 0.895 \exp(-0.0153\, T_s) \qquad (6)$$

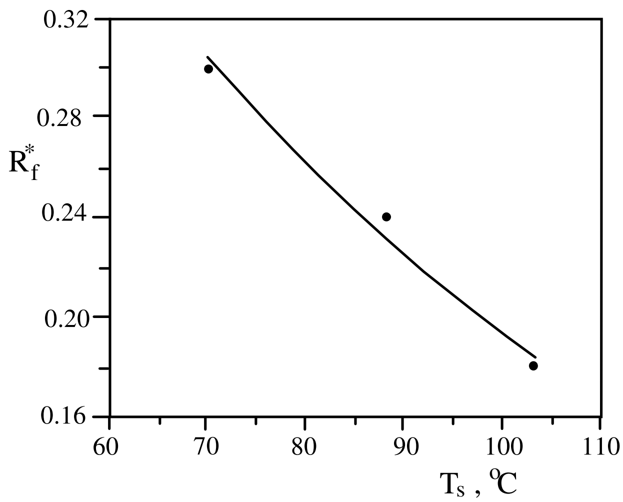

Fig. 7. Asymptotic fouling resistance, R_f^* as a function of T_s.

To perform the CF experimental run, the test liquid is changed with a 42 g/lit salt concentration seawater and the three heaters are replaced with new ones as mentioned before. Results are also represented graphically. Figures 8, 9 and 10 represent the variation of the crystalline fouling resistance with time for surface temperatures of 62, 84, and 106 °C respectively. In the first few hours, the fouling resistance appears to be small. Negative values of fouling resistance in the early stages have been observed when new surfaces have initially been exposed to fouling. As the fouling layer thickness increases, its thermal resistance increases due to the lower thermal conductivity of the fouling material.

It is clear that the fouling resistance increases linearly with time up to 30 hrs, and increases with increasing surface temperature. All the obtained fouling curves for the three surface temperatures are plotted together in Fig. 11 to show the difference between them. From these figures, it can be seen that:

- The obtained fouling resistance in this case is of linear type.

- The saw tooth effect is not present during the crystallization fouling test.
- The delay time is almost zero.
- At the beginning of operation, there is some improvement in the overall heat transfer coefficient due to the roughening of heat transfer surface.
- The fouling resistance values increase by increasing the surface temperature.

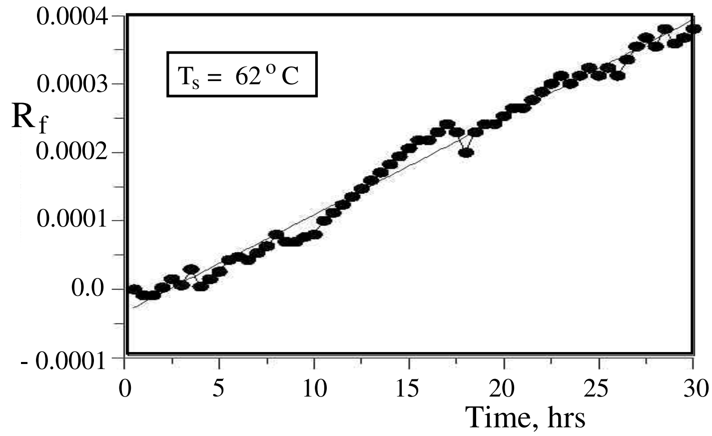

Fig. 8. Crystalline fouling curve for T_s = 62° C.

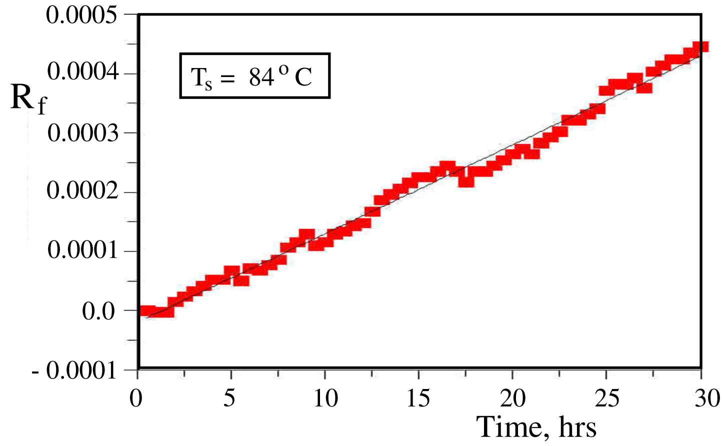

Fig. 9. Crystalline fouling curve for T_s = 84° C.

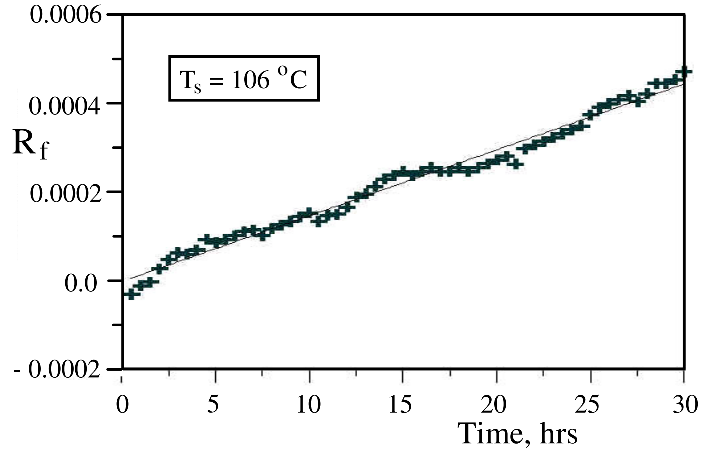

Fig. 10. Crystalline fouling curve for T_s = 106° C.

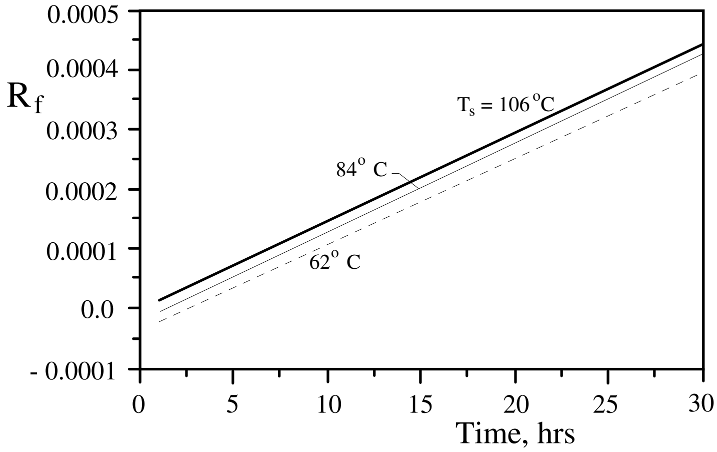

Fig. 11. Crystalline fouling curves for different T_s values.

Figure 12 shows the relation between the maximum fouling resistance (after 30 hrs of operation) and surface temperature. It can be seen that, the fouling resistance increases linearly with surface temperature. The relation between the fouling resistance and the surface temperature can be expressed as,

$$R_f = 1.3 \times 10^{-6}\ T_s + 0.00032 \qquad (7)$$

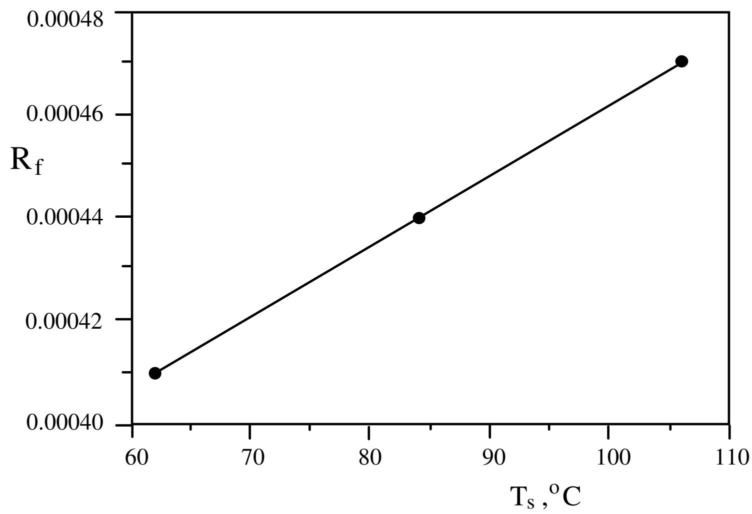

Fig. 12. Crystalline fouling curves for different T_s values.

In the case of PF increasing the surface temperature, the fouling resistance decrease, while, in the case of CF increasing surface temperature, the fouling resistance increases. This is because, in case CF, the stick ability or deposition probability factor for particles of salts is increased when the surface temperature in all times increases. While in case of PF, the stick ability of particles of rust is decreased when the surface temperature increases and vice versa in the case of CF in which the stick ability is increased by increasing the surface temperature.

CONCLUSIONS

The effect of surface temperature on both particulate and crystallization fouling of heat transfer surfaces has been studied. From this study, it can be concluded that;

1- The particulate fouling is of the asymptotic type and the crystallization fouling is of the linear type.
2- Increasing the surface temperature, decreases the fouling resistance in case of particulate fouling, and increases the fouling resistance in case of crystallization fouling.
3- For the particulate fouling type, the saw tooth effect is obtained.
4- The delay time is almost zero for both particulate fouling and crystallization fouling runs. This may be due to the high concentration in both cases.
5- At the beginning of operation, for both fouling modes, some improvement in the overall heat transfer coefficient is observed due to the roughening of heat transfer surface as a result of deposition of particles on this surface.

To decrease the effect of fouling and hence improve the performance of the heat transfer equipment, the following recommendations must be taken into account:

1- In the heat transfer equipment, the surface temperature must be as high as possible for PF and vice versa for crystallization fouling.
2- In the design of heat transfer equipment for certain operating conditions, the asymptotic fouling resistance must be taken into account for PF and maximum fouling resistance for crystallization fouling.
3- The fouling data have to be collected and analyzed from the industrial installations in the surrounding area to take the correct solution of the fouling problems.

For future research work, it is recommended to study the effect of the following:

1- The heat transfer surface material and geometry.
2- Solid particle concentration, type and size.
3- The fluid bulk temperature.

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