EFFECT OF SURFACE TEMPERATURE ON THE FOULING OF HEAT TRANSFER SURFACES

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ABSTRACT

The aim of the present work is to study the effect of surface temperature on the fouling rate. To carry out this study, an experimental setup has been designated and constructed. A Perspex test tube of 300 cm length and 5.53 cm inner diameter with three electric heaters fixed at the center is used as a test tube. Water with a solid particle concentration of 1gm/lit is used as a test fluid. The experimental runs have been carried out under different surface temperatures (from 55^{o}C to 95^{o}C) with a constant flow velocity of 0.08 m/s for about 280 hrs to reach the asymptotic fouling. The obtained results are represented in a graphical form and, show that the surface temperature has a great effect on the fouling resistance specially in the temperature range from 55^{o}C to 71^{o}C. This effect seams to be smaller when the surface temperature increases.

INTRODUCTION

Fouling in heat exchangers is the major reason for increasing energy consumption, maintenance, and operational costs. As deposition occurs, the flow area is reduced, which causes an increase in pressure drop across the apparatus [1-8]. Many types of fouling can occur on the heat transfer surfaces [1-17]. Based on the different physical and chemical processes involved, it is convenient to classify the fouling main types as:

1- **Precipitation Fouling:** Crystallization of dissolved salts due to solubility changes with temperature, and subsequent precipitation onto the heat transfer surface. Scaling belongs also to this type of fouling [18-20].
2- **Particulate Fouling:** Deposition of suspended particles in the process stream onto the heat transfer surfaces [13-16]. This process includes sedimentation where settling occurs under gravitational forces.
3- **Biological Fouling "biofouling":** This type occurs in raw water due to the attachment and growth of macroorganisms and/or their products on the heat transfer surfaces [21-23].
4- **Chemical Reaction Fouling:** Is a result of chemical reactions between reactants in the flowing fluid in which the surface material itself is not a reactant (e.g. in petroleum refining. polymer production and food processing).

5- Corrosion Fouling: Due to chemical or electrochemical reaction between the heat transfer surface itself and the fluid stream to produce corrosion products, which, in turn, change the surface thermal characteristics and foul it.

6- Solidification Fouling: Due to freezing of a pure liquid or a higher melting point components of a multi-component solution onto a cooler surface.

Fouling Curves:

The fouling process is indicated by the fouling resistance, R_f which is measured either by a test section or from the decreased capacity of an operating heat exchanger [2-4]. The results are presented by R_f time curve. The delay time, t_d indicates an initial period of time that can elapse where no fouling occurs. The most important fouling curves (Fig. 1) are:

1- The linear fouling curve

In this mode, the mass of deposition rate, m_d increases linearly with time and there is no deposition removal, m_r , or m_d - m_r = constant. The fouling curve in this case takes the form $R_f = a\,(t - t_d)$, where "a" is the slope of the line as shown in Fig. 1.

2- The asymptotic fouling curve

In this mode, the rate of fouling gradually falls with time, until a steady state is reached when there is an asymptotic fouling resistance, R_f^* is obtained. In practical industrial situations, the asymptote may be reached in a matter of hours, weeks or months depending on the operation conditions. The general equation describing this behavior takes the form $R_f = R_f^*\,(1 - e^{-\beta t})$.This mode is the most widely existed in the industrial applications.

3. The falling rate fouling curve

In this mode, the mass of deposit increases with time nonlinearly and without reaching a steady state of asymptotic value i.e. $m_d - m_r = f\ (t)$ and takes the form $R_f = f\ (t)$.

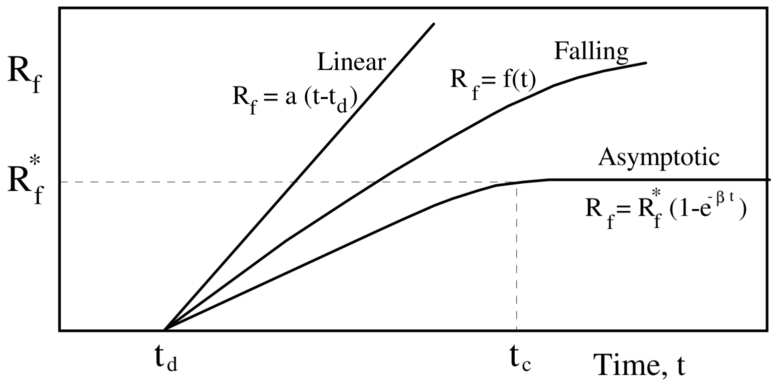

Figure 1. Fouling curves.

Parameters Affecting the Fouling:

The fouling characteristics of a fluid in contact with a heat transfer surface depends on the following main parameters,

1. Flow velocity of the fluid.
2. Surface temperature.
3. Fluid bulk temperature.
4. Material of the heat transfer surface.
5. Geometry of the heat transfer surface.
6. Characteristics of the fouling fluid.

LITERATURE REVIEW

Many investigators have studied the fouling phenomenon theoretically and experimentally. Kern and Seaton [1] have cited the first and the pioneer mathematical model for surface fouling. They stated that the fouling rate could be estimated as the difference between the deposition and removal rates. Taborek, et al. [6] introduced the water characterization factor to the deposition term to account for the effect of water quality. They expressed the deposition rate by the so called *Arrhenius* type equation. The removal term was postulated to be a function of shear stress, deposit thickness, and bonding strength of the deposit. Watkinson [7] reported experimentally the effect of fluid velocity on the asymptotic fouling resistance for three different operating foulants and obtained a correlation for each.

Beal [14] described a new and potentially promising method for predicting the deposition of particles entrained in turbulent flow as a function of concentration gradient in normal direction times the sum of molecular and eddy diffusivity. 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. Recently, Webb and Li [24] investigated the effect of internal tube enhancement on the fouling rate for cooling tower water. They found that the enhancement parameters such as helix angle and number of starts have significant effects on the fouling mechanism. It is observed that, fouling increases as the number of starts and helix angle increases. Li and Webb [25] extended their pervious work to study the effect of different fouling types. A comparison between pure particulate fouling and combined precipitation and particulate fouling had been carried out. They found that, the fouling resistance due to pure particulate fouling is less than that due to the combined precipitation and particulate fouling. Kim, *et al* [26], investigated the effect of electronic anti-fouling (EAF) technology on fouling mitigation in a heat exchanger in an open cooling tower systems. They found that, the fouling resistance with EAF treatment was about 70% less than that without EAF treatment, at the end of 270-hr tests.

The effect of surface temperature on the surface fouling has been mentioned in several studies [2,3,8,10]. These studies indicate that the role of temperature effect is not well defined. The literatures show that *"increased temperature may increase, decrease, or* *have no effect on the amount of material depositing at a surface".* This difference in behavior does indicate the importance of temperature for our understanding of particle fouling. On the light of the previous review and brief discussion shown above the effect of surface temperature on fouling of heat exchangers was not completely considered neither theoretically nor experimentally. Therefore, the present work deals with the effect of surface temperature on fouling of heat exchangers equipments.

EXPERIMENTAL SETUP

To study the effect of surface temperature on the fouling rate, a new technique is employed to measure the fouling and asymptotic resistances. Three electric heaters with different surface temperatures are fixed inside a test tube as shown in Fig. 2. Each heater is subjected to the same flow velocity, foulant concentration and foulant material. The test tube (3 m length) is made from a transparent material for visual observation. The test tube is a part of a closed loop piping and a water tank as shown in the figure.

The pump extracts the water from the tank to the test tube. After passing through it, the water returns back to the tank, cooled with an open cooler to the same original temperature before entering the test tube again. The experimental setup has been designed, constructed, in the Hydraulic Machines Laboratory, Faculty of Engineering, Mansoura University. The test rig has the following specifications:

Tube material	Pure Perspex
Outer diameter	5.92 cm
Inner diameter	5.52 cm
Total length o tube	300 cm
Diameter of the heaters	1.2 cm
Length of heater 1 (500 W)	35 cm
Length of heater 2 (1000 W)	45 cm
Length of heater 3 (1500 W)	65 cm

Handle valves are used to control the flow rate, which is measured by the aid of a calibrated rotameter. The test section is suitably instrumented to measure the mean surface temperature of each heater, the bulk water temperature between heaters, and the tank water temperature. The locations of the thermocouples are decided depending on the previous studies of investigators. The temperatures are recorded with a multi-point temperature recorder that is a self-balancing, automatic and manual switching, with a sensitivity of $0.01^{o}C$.

A low speed fan is fixed to the tank cover to stir the fouling material in the water before entering the test tube (is not shown in the figure). Since the flow rate of water entering the tank is equal to that leaving; the water level in the tank remains unchanged. The water that used in this experiment is from the River Nile.

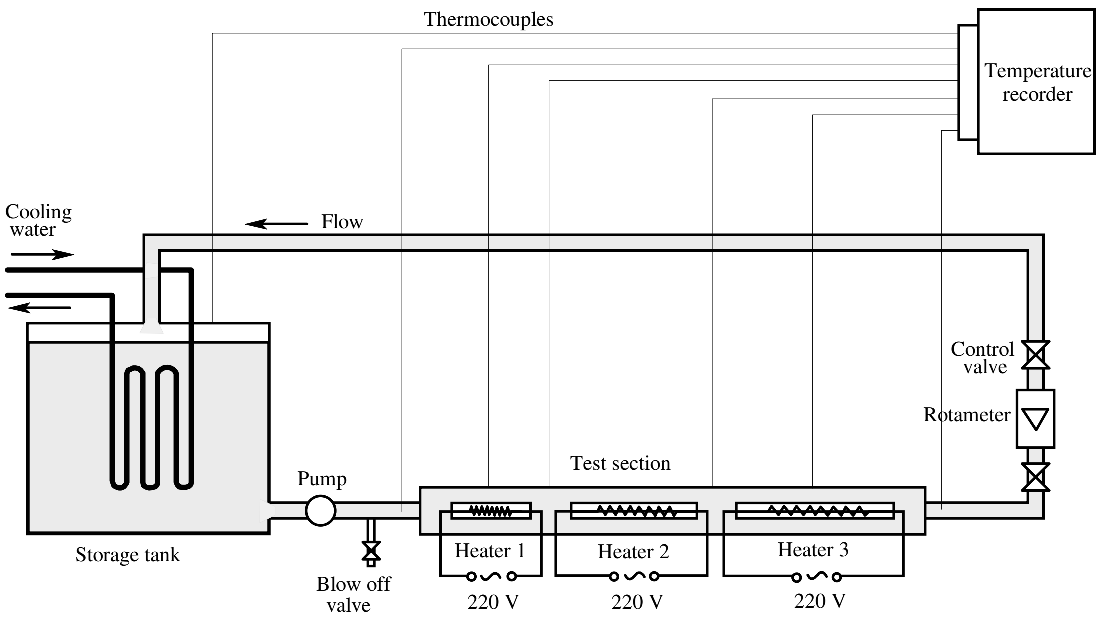

Figure 2. Layout of the experimental setup.

Experiment Procedure

The main purpose of this experimental work is to measure the fouling resistance and asymptotic resistance. To carry out this study, the system is subjected to some preliminary tests to ensure proper operation and avoid any leakage from the components. When the experiment is started, the water is pumped to the test section to flow over the three heaters of different surface temperatures to allow heat exchange between them and the test fluid. The flow rate is controlled by control valves to keep constant flow velocity at 0.08 m/s in all runs. Then the water leaves the test tube to the rotameter, which measures the flow rate. Temperatures are measured by copper-constantan thermocouple (type T). The data are recorded half hour intervals over 280 hours in the period from 16/6/2005 to 16/12/2005. Experiments are carried out in two groups (I and II) with six surface temperatures from 55 to 95^{o}C.

The concentration of the solid particles in the tested water is prepared and controlled to keep it constant during all experimental runs. The concentration is tested regularly by a turbid meter (model 2100 A). Make up solid particles or pure water are added to the water in the storage tank to keep the concentration constant. 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 a bolters of size under 70 μm. Then it is tested and calibrated in the chemical laboratory. The best concentration to keep the solid particles in colloidal solution is 1 gm/lit. To insure the colloidal solution, filtration papers that give a maximum particle size of 45 μm are also used.

GOVERNING EQUATIONS

A computer program is prepared to calculate the fouling resistance using the measured inlet and exit bulk water temperatures across each heater in the test section, the surface temperatures of the three heaters, and the eater mass flow rate. The fouling resistance, R_f is determined by subtracting the fouling resistance when the test section is clean (at time zero) from that when fouled,

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

Where, U_c and U_f are the overall heat transfer coefficients for clean and fouling conditions respectively.

These coefficients are calculated from the general heat transfer equation $Q = U\,A\,\Delta\theta_m$ as,

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

$$U_f = \left(\frac{Q}{A\,\Delta\theta_m}\right)_f \tag{3}$$

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

$$Q = \dot{m}\,C_p\,(T_o - T_i) \tag{4}$$

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

$$\Delta\theta_m = \frac{(T_s - T_i) - (T_s - T_o)}{\mathrm{Ln}\left((T_s - T_i)/(T_s - T_o)\right)} \tag{5}$$

As mentioned before, the most common and widely practically existing fouling type is the "asymptotic" mode. This type of fouling can be described by an exponential equation as,

$$R = R_f^*\,(1 - e^{-\beta t}) \tag{6}$$

Where,

R^*_f is the asymptotic fouling resistance. ($m^2.^oC/kW$)

t_c is the time constant, hr

$\beta = 1/t_c$

The percentage reduction in U_c due to fouling is given by,

$$\Delta U = \frac{U_c - U_f}{U_c} * 100\% \tag{7}$$

Combining with equation (1) yields,

$$\Delta U = \frac{U_c R_f}{1 + U_c R_f} * 100\% \tag{8}$$

The change in asymptotic fouling resistance ΔR_f^* can be also determined.

RESULTS AND DISCUSSIONS

Each experimental run is carried out under a constant surface temperature. The experiments are divided into two groups (I and II) at surface temperatures ranging from 55°C to 95°C. In the first group (I), the fouling is tested at temperatures of 75, 85 and 95°C, where the fouling is tested at temperatures of 55, 65 and 71°C in the second group (II). The runs are carried in a differential order to insure the same operating conditions. In order to monitor an approximate value of the asymptotic fouling resistance, each run takes 280 hours net working time and terminated when the fouling resistance approached an asymptotic value.

The experimental results represent graphically the fouling resistance R_f, as a function of time. Figures (3, 4, 5, 6, 7, and 8) show the variation of R_f with time for surface temperatures of 55, 65, 71, 75, 85 and 95°C respectively. Figure 2.a shows the variation of R_f for a surface temperature 55°C of the heater 1. The broken line connecting the points to show the "saw teeth" effect nature of the fouling, which is observed in all the experimental runs. This effect is a result of partial removal of some deposits due to "sapling" or "sloughing" followed by a rapid build up of deposits. In the last 50 hours, the fouling resistance appears to be approximately constant and the asymptotic fouling resistance is almost obtained (R_f^* = 0.69 m^2.°C/kW). The average curve of the measured data is plotted by a dashed line in order to show the trend of fouling.

In the first 35 hours, the fouling resistance appears to be small. 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. Figure 3.b shows the variation in the fouling resistance for the first 75 hours to demonstrate this effect.

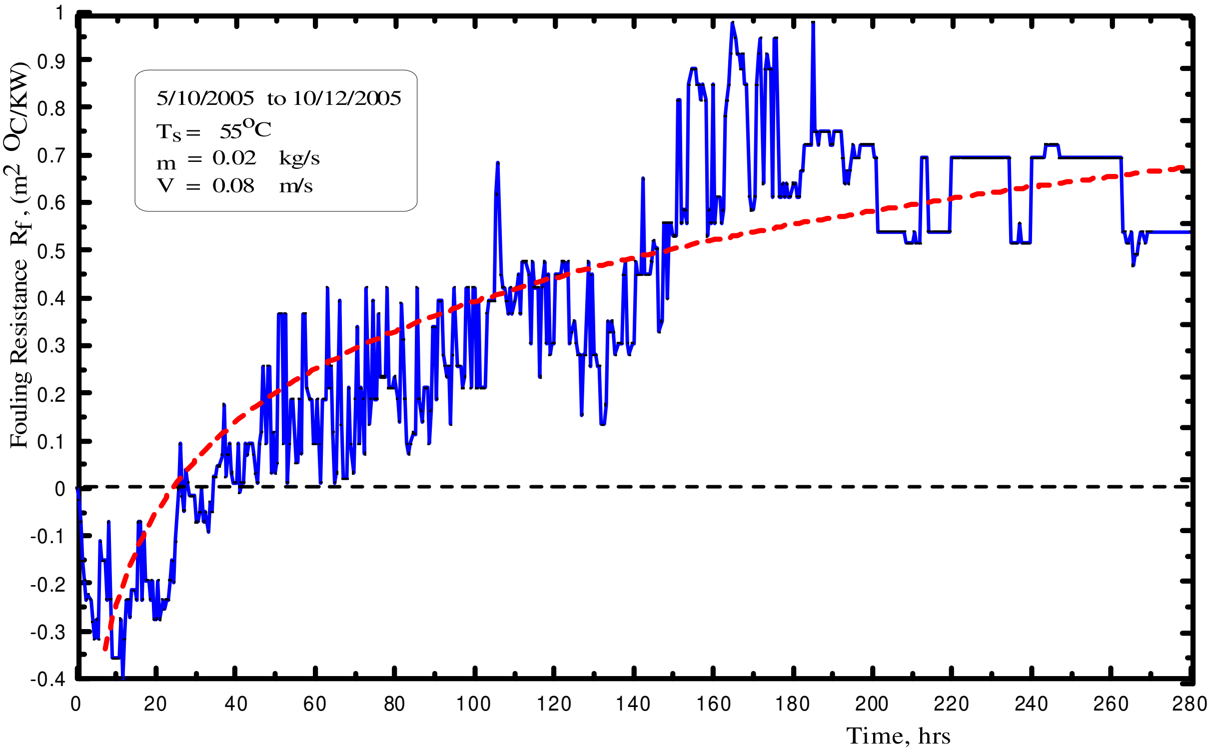

Figure 3.a. The fouling curve of heater 1/II (T_s=55°C).

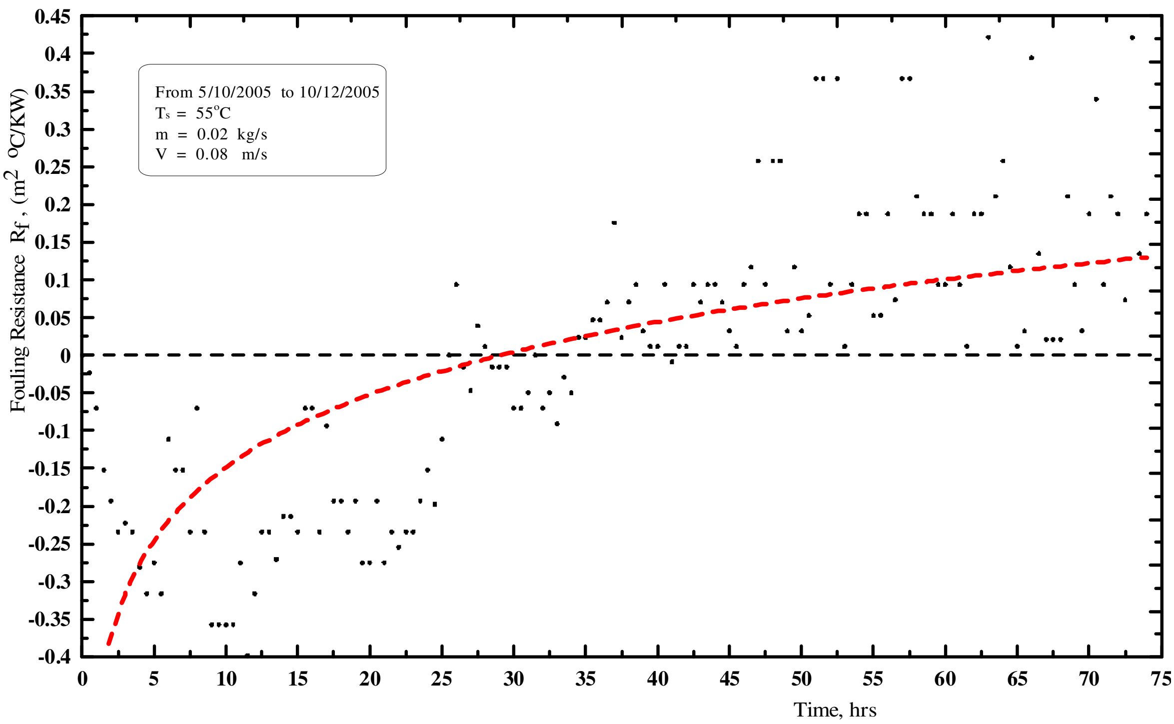

Figure 3.b. The fouling curve of heater 1/II (T_s=55°C) at the first 75 hours.

Figure 4 shows the same results for the heater (2) with a surface temperature of 65°C. The figure shows that the fouling resistance increases with time during the first 190 hours of operation, and tends to be constant during the last 90 hours where the asymptotic fouling resistance (R_f^*=0.66 m^2.°C/kW) is approximately achieved. The asymptotic fouling resistance is less than that of surface temperature 55°C by about 4.35%. Figure 5 shows the results for heater (3) at surface temperature 71°C. One can see that, the fouling resistance increases with time during the first 180 hours of operation, and tends to be constant during the last 100 hours where the asymptotic fouling resistance is achieved (R_f^*=0.51 m^2.°C/kW). The asymptotic fouling resistance at this surface temperature is less than that of surface temperature 55°C by about 26.1%, and less than that of surface temperature 65°C by about 22.72%.

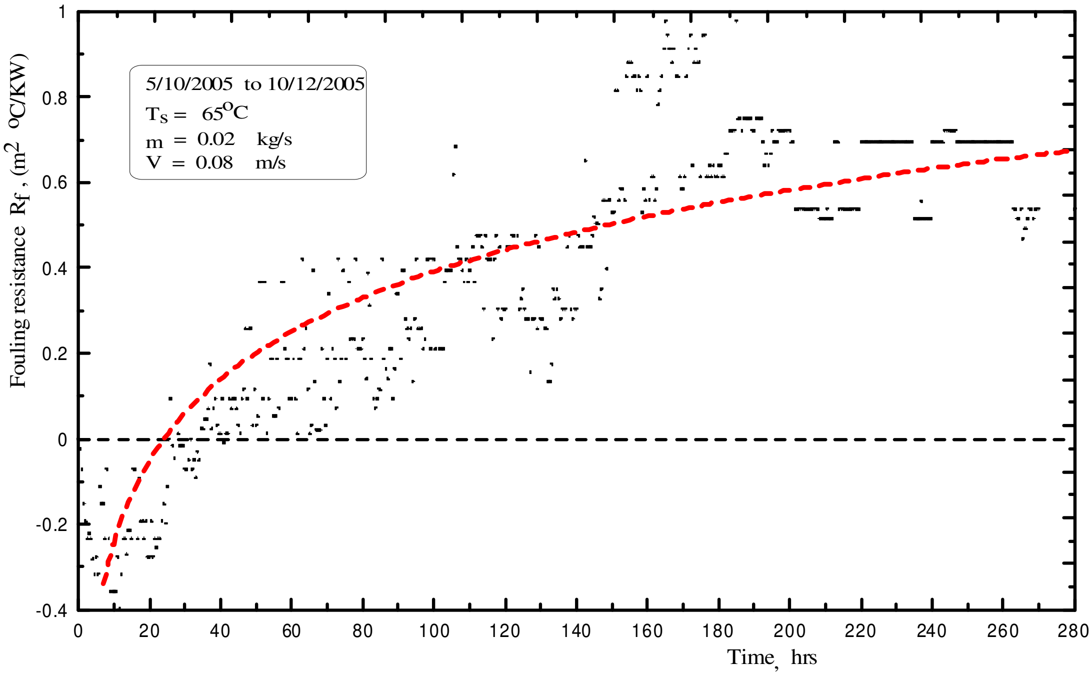

Figure 4. The fouling curve of heater 2/II (T_s=65°C).

For a surfaces temperature of 75°C (Figure 6), the fouling resistance increases with a slower rate than that of the above three lower surface temperatures. The asymptotic value in this case (R_f^*=0.21 m^2.°C/KW) is achieved after about 220 hrs of operation. This value is smaller by about 59.5% than that of surface temperature 55°C

For a surface temperature of 85°C (Figure 7), the fouling resistance is seen to be smaller. The asymptotic value (R_f^*=0.19 m^2.°C/KW) is achieved after about 200 hrs of operation. This asymptotic value is smaller than that of surface temperature 55°C by about 74.46%. For a surface temperature of 95°C, (Figure 8) the fouling resistance is smaller than that of all the surface temperatures. The asymptotic value (R_f^*=0.12 m^2.°C/KW) is achieved after about 220 hrs operation, and is smaller than that of surface temperature 55°C by about 82.6%.

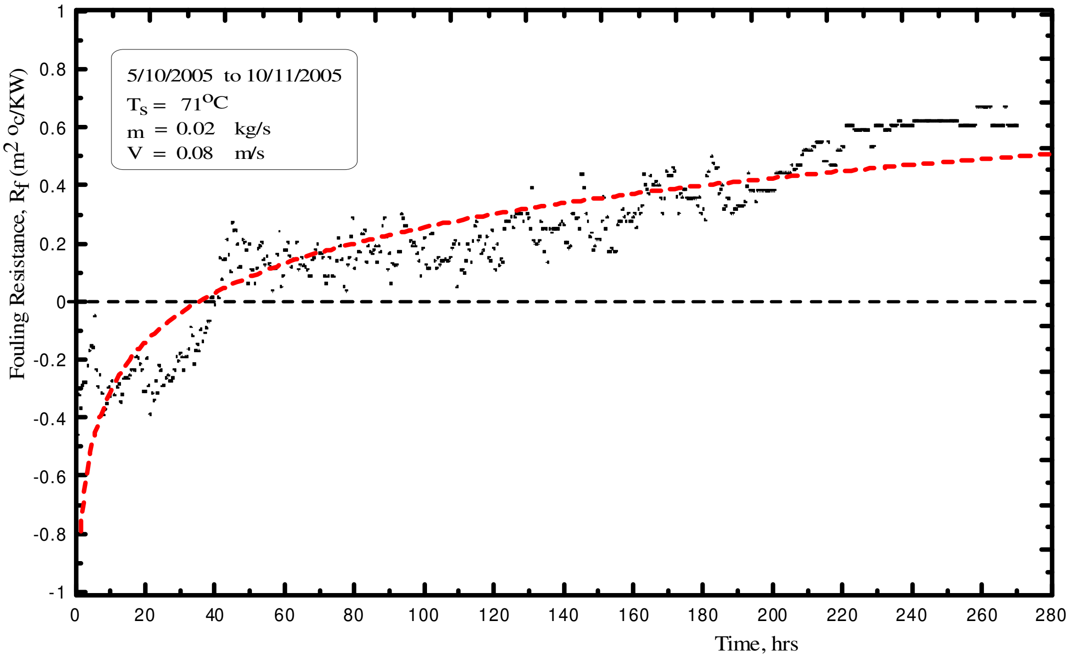

Figure 5. The fouling curve of heater 3/II (T_s=71°C).

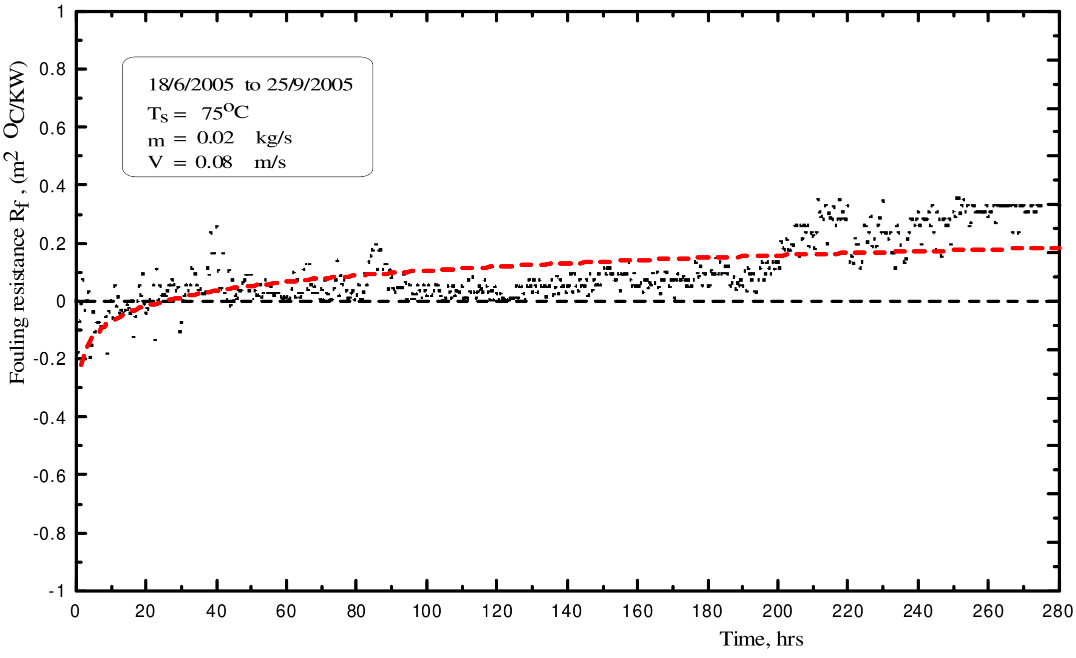

Figure 6. The fouling curve of heater 1/I (T_s=75°C).

Figure 9 shows all the fouling curves plotted together on the same graph to enable comparison between them. From this figure, it can be seen that:

- Both the fouling resistance and asymptotic values decrease by increasing surface temperature.
- The fouling in this case is of the asymptotic type.
- The delay time is almost zero for all cases.

- At the beginning of operation, there is some improvement in the overall heat transfer coefficient due to the roughening of heat transfer surface.
- At the first 45 hrs, the effect of surface temperature on the fouling resistance is irregular.

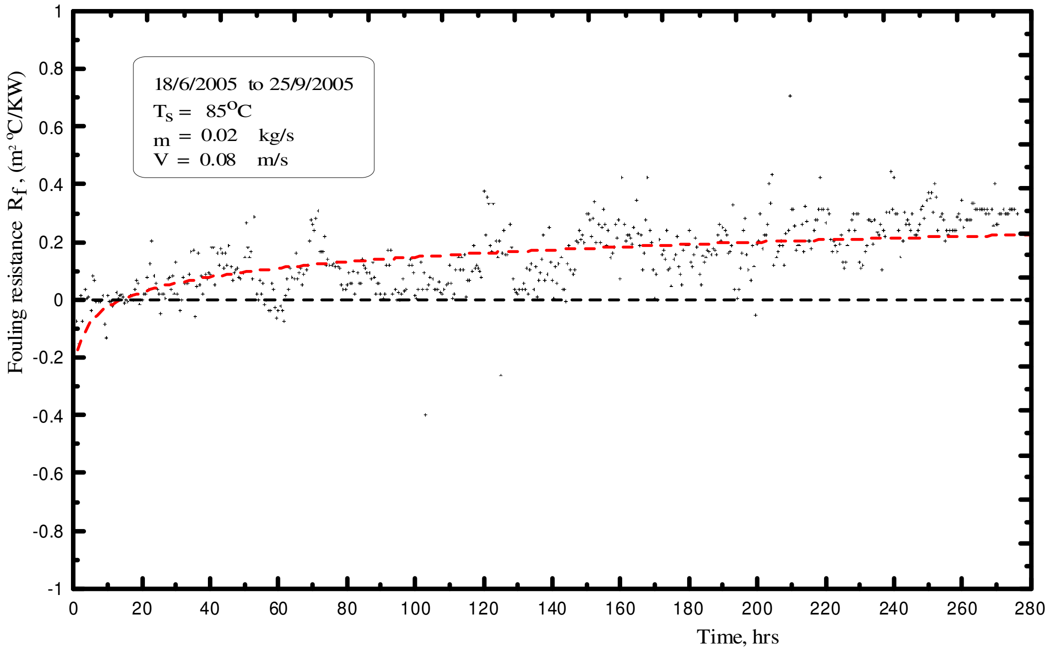

Figure 7. The fouling curve of heater 2/I (T_s=85°C).

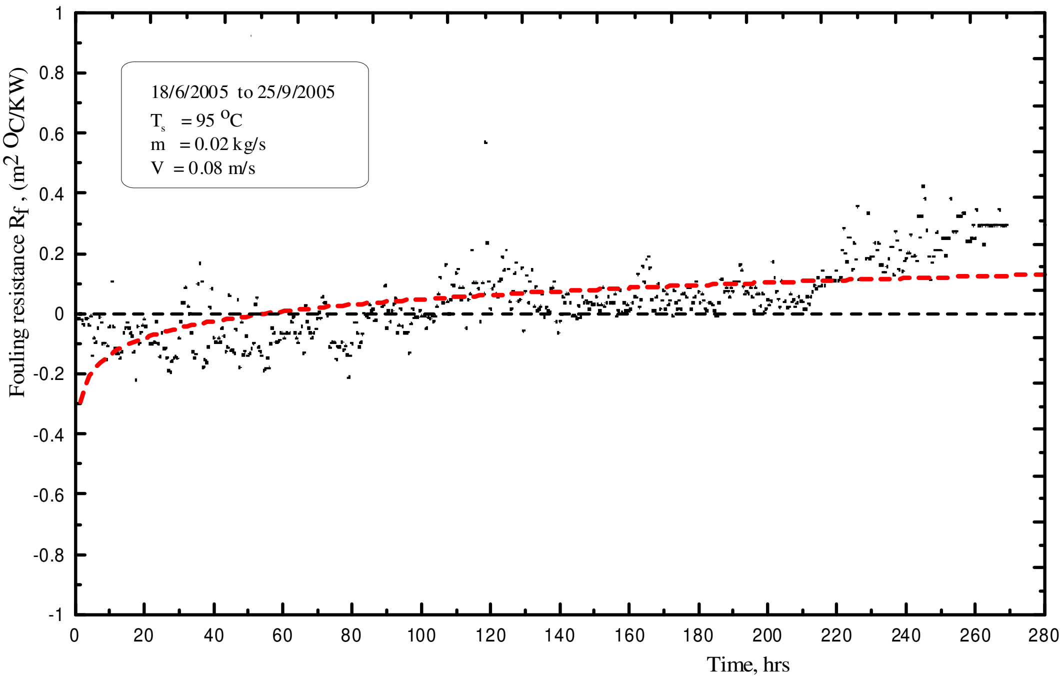

Figure 8. The fouling curve of heater 3/I (T_s=95°C).

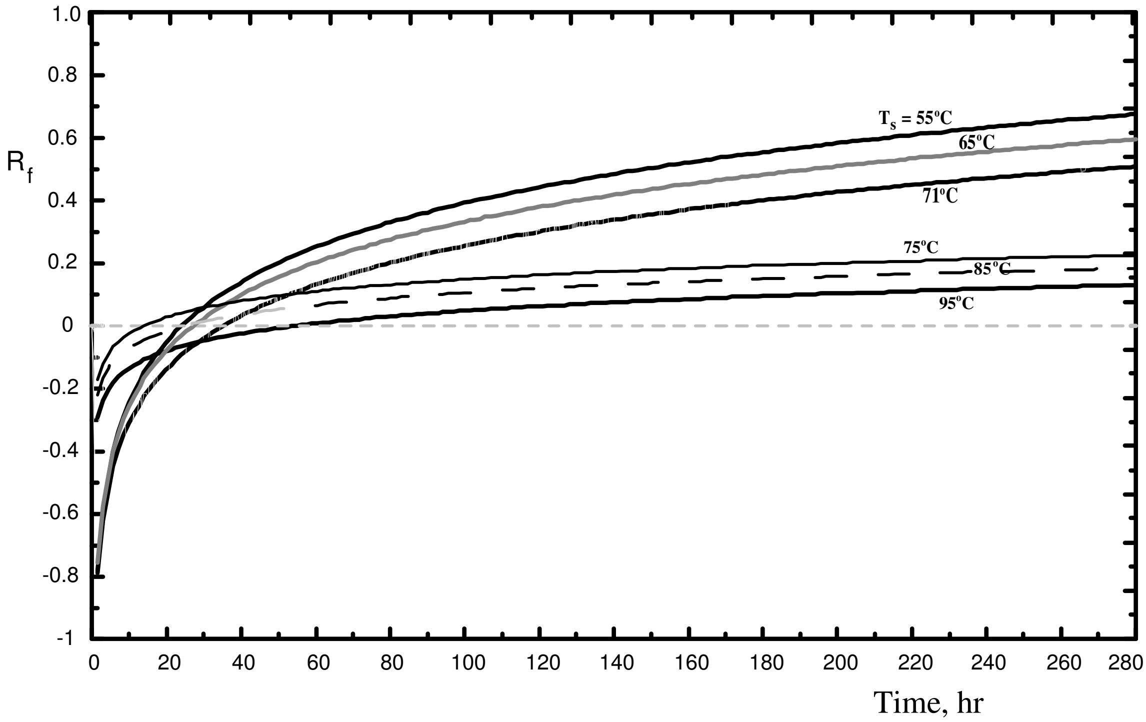

Figure 9. The fouling resistance as a function of time for all runs.

Figure 10 shows the relation between the asymptotic fouling resistance and the surface temperature. From this figure, it can be seen that, the asymptotic fouling resistance decreases as the surface temperature increases under the same operating conditions. The solid curve represents the empirical equation $1265477.1\ e^{-3.53699244\ T_s}$, which is the best fit to the experimental results.

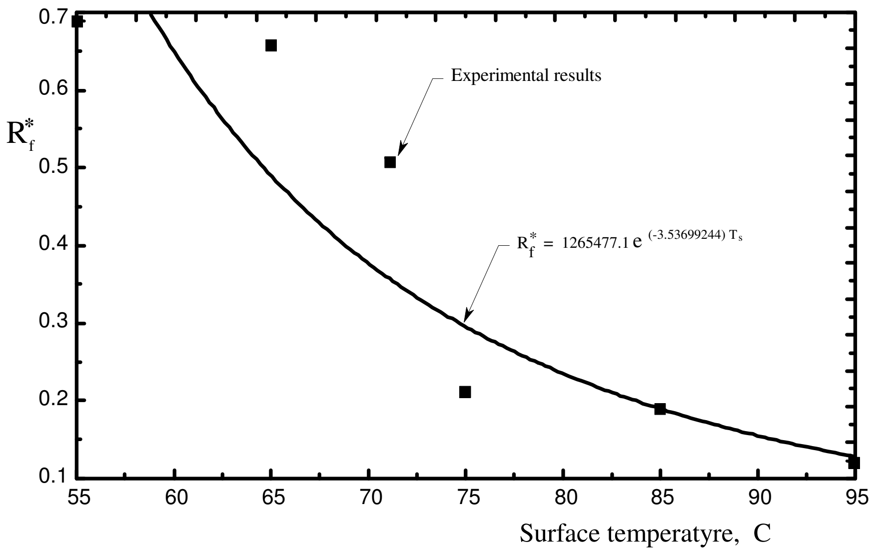

Figure 10. The change of the asymptotic fouling resistance with surface temperature

It can be observed from the above figures that there is a good agreement between the experimental data (the average curve of the experimental results) and the curves of the asymptotic equation for the same surface temperature.

The asymptotic fouling resistance at each surface temperature and the percent decrease in it when increasing the mean surface temperature are summarized in Table 1. Based on the experimental results, the parameters of the asymptotic equation for each surface temperature are represented also in this table. The percentage reduction in the overall heat transfer coefficient is calculated from equation (8) at the end of experiment ($R_f = R_f^*$) for each surface temperature.

Table 1. Summary of results

T_s °C	U_C (kW/m^2°C)	ΔU_C %	R_f^* (m^2.°C/kW)	ΔR_f^* %	t_c hr	$\beta = 1/t_c$ (hr^{-1})
55	1.2376	46.1	0.69	0.0	230	0.0125
65	1.4272	48.6	0.66	4.35	185	0.0118
71	1.4433	42.4	0.51	26.10	150	0.0087
75	1.9964	29.5	0.21	59.56	100	0.01
85	2.114	28.7	0.19	74.46	90	0.011
95	1.924	18.8	0.12	82.60	120	0.0083

CONCLUSIONS

The effect of surface temperature on the fouling of heat transfer equipment has been experimentally studied. The setup is constructed with a test tube of 300 cm length and 5.53 cm inner diameter and three different electric heaters fixed at the center. Water with a solid particle concentration of 1 gm/lit is used as a test fluid with a constant flow velocity of 0.08 m/s. The fouling curves are obtained for the same operating conditions and different surface temperature from 55°C to 95°C, the following results can be concluded as:

1. Increasing the surface temperature decreases both the fouling and the asymptotic fouling resistances. This effect is more pronounced at lower temperatures.
2. The obtained fouling mode is of the asymptotic type.
3. The delay time is almost zero in this case.
4. The saw tooth effect is observed in all the experimental runs.
5. At the beginning of operation, the observed improvement in the overall heat transfer coefficient is due to the roughening of heat transfer surface as a result of deposition of particles on it.

The data collected from the present work is seen to be important in the practical applications. A future work with other fluids and particle concentrations is recommended. The need of extensive theoretical analysis of the fouling problem is also essential.

NOMENCLATURE

A	Heat transfer area, *m^2*
C_p	Specific heat circulating water, *$kW/kg.\,^oC$*
L	Heaters length, *35, 45, 65 cm*
$\dot{m}_f$	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, *$kkW/m^2.^oC$*
Q	Heat transfer rate, *kW*
t	Time, hours
t_c	Time constant, hours
T_i	Fluid inlet temperature, *^oC*
T_o	Fluid outlet temperature, *^oC*
T_s	Surface temperature, *^oC*

Greek letters

β	$= 1/t_c$
$\Delta\theta_m$	Logarithmic mean temperature difference, *^oC*
ΔU	Percentage change in the overall heat transfer coefficient due to fouling.
ΔR_f^*	Percentage change in the asymptotic fouling resistance.

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