Mansoura Engineering Journal, (MEJ), Vol. 32, No. 1, March 2007.

# Effect of Flow Velocity on the Surface Fouling

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## ملخص البحث

### تأثير سرعة السريان على الترسيبات فوق أسطح إنتقال الحرارة

إن سرعة السريان تعد من أهم العوامل التي تؤثر على معدل الترسيبات فوق أسطح إنتقال الحرارة. و في هذه الدراسة قد تم إعداد دراسة عملية لدراسة تأثير سرعة السريان على معدل الترسيب فوق أسطح إنتقال الحرارة بإستخدام الترسيب الرقائقي. وقد تم إجراء جميع التجارب تحت درجة حرارة ثابتة بإستخدام البخار كوسيط تسخين. و في هذه التجارب كان تركيز المواد العالقة بمياة التبريد 1 جم / لتر و كانت سرعات السريان تتراوح من 0,24 إلى 1,42 م/ثانية و كان زمن التجربة طويل ( حوالي 200 ساعة) و ذلك للحصول على أقصى قيمة للترسيبات (قيمة التقارب).

وقد أظهرت النتائج أن كل من معدل الترسيب و أقصى قيمة للترسيب تقل بزيادة سرعة السريان. و كان الزمن الذي يسبق حدوث الترسيب بعد بدأ التجربة صغير جدا ويكاد يصل للصفر. وقد لوحظ حدوث ظاهرة أسنان المنشار ( والتي تحدث كثيرا مع هذا النوع من الترسيب) في جميع التجارب. و كان تأثير سرعة السريان كبيرا جدا للسرعات من 0,24 حتى 0,35 م/ثانية و يقل هذا التأثير للسرعات الأعلى وخاصة في مدى السرعات من 1,21 حتى 1,42 م/ثانية.

## Abstract

*The flow velocity is one of the most important parameters affecting the fouling rate on the heat transfer surfaces. An experimental study is carried out to investigate the effect of flow velocity on the surface fouling for the particulate fouling type. The experiments are carried out under constant surface temperature by using the steam as a heating medium. Water with a solid particle concentration of 1 gm/lit is used as a test fluid and the test flow velocities are ranged from 0.24 to 1.42 m/s. The runs have been operated for a long time period (about 200 hrs) to attain the asymptotic fouling resistance.*

*The obtained experimental results showed that; increasing the flow velocity decreases both the fouling resistance and the asymptotic fouling resistance. The delay time is very small and it seems to be zero. The saw tooth effect has been obtained in all runs. There is a great effect of flow velocity on the fouling resistance due to velocities in the range from 0.24 to 0.35 m/s where this effect is seen to be smaller when the flow velocity increases from 1.21 to 1.42 m/s.*

## Nomenclature

| | |
|---|---|
| A | heat transfer surface area, *m²* |
| $A_c$ | heat transfer surface area for clean condition, $m^2$ |
| $A_f$ | heat transfer surface area for fouled condition, $m^2$ |
| $Cp_{cw}$ | cooling water specific heat, $kJ/kg.^{o}C$ |
| $d_i$ | test tube inner diameter, *mm* |
| $d_o$ | test tube outer diameter, *mm* |
| L | tested section length, *m* |
| $\dot{m}_{cw}$ | cooling water mass flow rate, *kg/s* |
| Q | heat transfer rate, *W* |
| $R_f$ | fouling resistance, $m^2.{}^{o}C/W$ |
| $R^*_f$ | asymptotic fouling resistance, $m^2.{}^{o}C/W$ |
| t | time, *s* |
| $t_c$ | time constant, *s* |
| $T_{cwi}$ | cooling water inlet temperature, $^{o}C$ |
| $T_{cwo}$ | cooling water outlet temperature, $^{o}C$ |
| $T_s$ | steam temperature, $^{o}C$ |
| U | overall heat transfer coefficient, $W/m^2.{}^{o}C$ |
| $U_c$ | overall heat transfer coefficient for clean condition, $W/m^2.{}^{o}C$ |
| $U_f$ | overall heat transfer coefficient for fouled condition, $W/m^2.{}^{o}C$ |
| $\Delta T_m$ | logarithmic mean temperature difference, $^{o}C$ |

Accepted March 18, 2007

## 1.Introduction

Fouling of heat transfer surfaces is defined as the deposition and accumulation of unwanted materials on the heat transfer surfaces, increases the overall resistance to heat transmission and reduces the performance and efficiency of the heat transfer equipments [1]. In industry, fouling affects both capital and operating costs of heat exchangers and causes a considerable additional costs such as energy losses due to the decrease in the thermal efficiency, losses of production during shut down for cleaning. Using the recommended fouling factors by TEMA [2] for a typical water-water heat exchanger, the heat transfer surface area may be increased by 100 %. The overall cost of fouling in the United Kingdom was estimated to be 0.5 % of the Gross National Product [3]. In the USA the cost of fouling was estimated as US$ 1400 M per year [4].

There are many types of fouling that can occur on the heat transfer surfaces [5]. The main types are; precipitation fouling, particulate fouling, biological fouling, chemical reaction fouling, corrosion fouling and solidification fouling. The factors affecting the fouling depositions are [6]; fluid flow velocity, surface temperature, fluid bulk temperature, heat transfer surface material, characteristics of the fouling fluid and geometry of the heat transfer surface. The fouling resistance, $R_f$, is determined from the overall heat transfer coefficient of the fouled and clean surfaces as:

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

The overall fouling process is indicated by the fouling resistance (called fouling factor), $R_f$, which is measured by a test loop or from the decreased capacity of an operating heat exchanger. The results are presented as the fouling factor-time curve. This curve can take different modes as linear curve ( $R_f = a\ t$), falling rate curve or the asymptotic curve which represented mathematically as:

$$R_f = R^{*}_f (1 - e^{-t/tc})$$

Many investigators have studied the fouling phenomenon theoretically and experimentally. Watkinson, et al., [7], obtained a set of experimental fouling-time curves and compared there results with the theoretical fouling model proposed by Kern and Seaton [8]. It was found that, the initial fouling rate was inversely proportional to the mass flow rate and dependents exponentially on the initial wall temperature. They reported also that, the asymptotic fouling resistance was inversely proportional to the squared mass flow rate. Webb and Li, [9,10], investigated the effect of internal tube enhancement on the 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., [11], 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 hours test.

From the previous studies and the literature work, the effect of the flow velocity on the fouling deposition is limited. Therefore, in the present work, the effect of flow velocity on the surface fouling is investigated and studied.

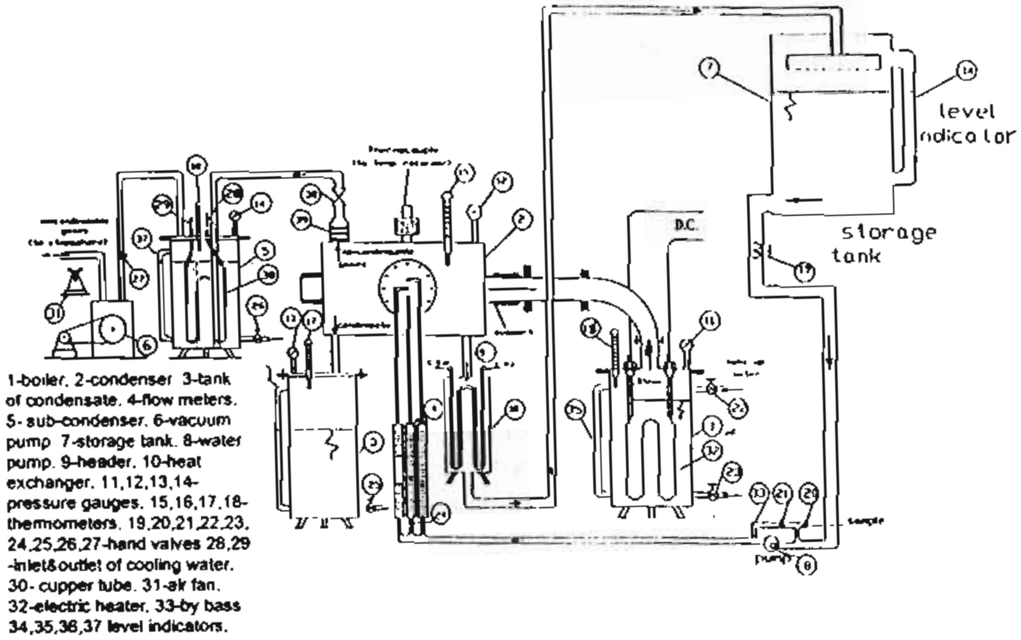
## 2. Experimental work

A differential technique has been developed and an experimental test rig is designed and used for measuring the fouling resistance. Fig.(1) shows a schematic diagram of this set up. The set up is designed to simulate the operating conditions of the most widely used heat transfer equipment. The condenser has three copper tubes (Cu-Ni 97%}, outer diameter 19 mm, inner diameter 16 mm, total length 2400 mm and test section length 300 mm. The test section is chosen to be at the middle of the test tubes, where the surface temperature is almost uniform. The interance length is long enough (1100 mm) to yield hydraulically and thermally fully developed flow in the test section. The three test tubes are used to study the effect of flow velocity on fouling deposition where each tube has a different flow velocity. The cooling water (which has used as a test fluid) flow rate in each tube is controlled and measured with hand valve and rotameter respectively. The experiments were carried out under constant particle concentration in a closed loop. In the preparation of the test fluid and to have a colloidal solution, it was found that the solid particle concentration was 1 g/lit. The concentration was measured and controlled to give a colloidal solution using filtration papers giving a maximum particle size of 45 μm. The particle concentration of 1g/lit was kept constant during all runs. Fig.(2) shows the closed loop of the cooling water. The cooling water is cooled in a heat exchanger and returned back to a storage tank to be recirculated again with a pump. Dry saturated steam generated by the boiler is used in the condenser. The steam loop and the condenser are thermally insulated. The pressure and temperature of the steam are measured and kept constant during the runs. The mean temperature of the test tubes surface and the bulk mean temperature of the cooling water entering and leaving the test tubes are measured by thermocouple type E. The thermocouples are connected to a calibrated digital electronic temperature recorder. The experiments are carried out in two groups with six different flow velocities ranging from 0.24 to 1.42 m/s. The values of these velocities are given in table (1).

Table (1). Test parameters of the experimental runs.

| Group no. | Test section no. | Velocity, *m/s* | Flow rate, *kg/hr* |
|---|---|---|---|
| I | 1 | 1.21 | 875 |
|  | 2 | 0.62 | 450 |
|  | 3 | 0.35 | 250 |
| II | 1 | 1.42 | 1030 |
|  | 2 | 0.51 | 370 |
|  | 3 | 0.24 | 170 |

The inlet and exit cooling water temperatures across the three test sections are measured for each velocity at intervals of 1 hour and the net working time for each group was about 200 hours. The pressure and temperature of the saturated steam were measured and controlled to be constant at atmospheric pressure and 100°C during all runs. Therefore, the test sections surface temperature was kept constant for all runs.



1-boiler. 2-condenser 3-tank of condensate. 4-flow meters. 5- sub-condenser. 6-vacuum pump 7-storage tank. 8-water pump. 9-header. 10-heat exchanger. 11,12,13,14- pressure gauges. 15,16,17,18- thermometers. 19,20,21,22,23, 24,25,26,27-hand valves 28,29 -inlet&outlet of cooling water. 30- cupper tube. 31-air fan. 32-electric heater. 33-by bass 34,35,36,37 level indicators.

Fig.(1). Layout of the experimental set up

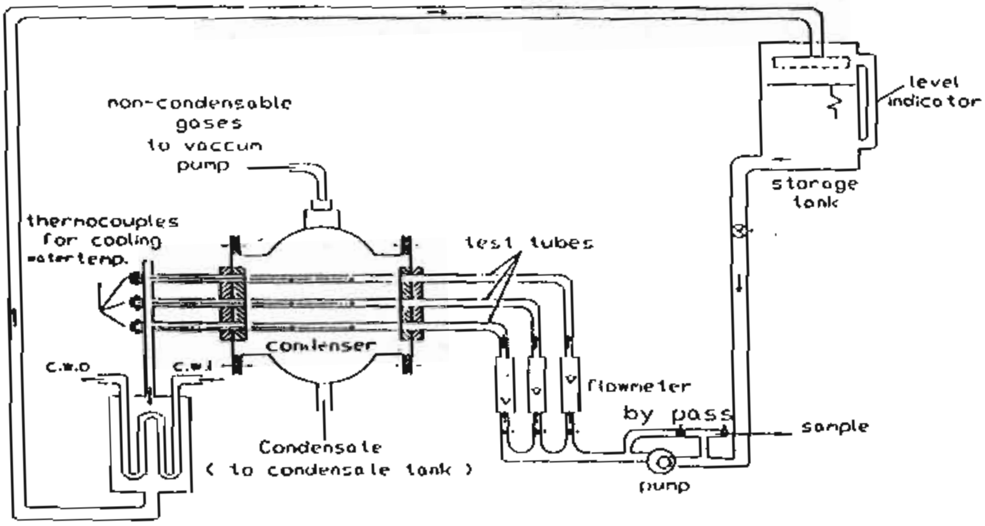


Fig.(2). Cooling water closed cycle

## 3. Results and Discussions

The experiments have were out to study the effect of flow velocity of (cooling water) on the fouling resistance, $R_f$ and on the asymptotic fouling resistance, $R^*_f$. A total of six velocities are tested using the city water after distillation and addition of solid particles. The fouling resistance is determined by subtracting the overall thermal resistance when the test section is clean (at start of the run, zero time) from that when it is fouled (at time *t*) as follows:

$$R_f = (1/U_f) - (1/U_c) \qquad (1)$$

The overall heat transfer coefficient for both clean, $U_c$, and fouled, $U_f$, conditions are given from the following governing equations:

$$Q = m^{\cdot}_{cw}\, Cp_{cw}\, (T_{cwo} - T_{cwi}) = U\, A\, \Delta Tm \qquad (2)$$

$$\Delta Tm = [(T_s - T_{cwi}) - (T_s - T_{cwo})] / \ln [(T_s - T_{cwi}) / (T_s - T_{cwo})] \qquad (3)$$

$$A = \pi\, (d_i + d_o) L/2 \qquad (4)$$

$$U = Q/A\, \Delta Tm \qquad (5)$$

$$1/U_c = (A\, \Delta Tm/Q)_c \qquad (6)$$

$$1/U_f = (A\, \Delta Tm/Q)_f \qquad (7)$$

$U_c$ and $U_f$ are measured at the same thermal-hydraulic conditions.
Substitute from equations (2) - (7) in eqn. (1) then;

$$R_f = (A\, .\, \Delta Tm/Q)_f - 1/U_c \qquad (8)$$

$$R_f = [A\{((T_s - T_{cwi}) - (T_s - T_{cwo}))/\ln((T_s - T_{cwi})/(T_s - T_{cwo}))\} * 1/(m^{\cdot}_{cw}\, Cp_{cw}\, (T_{cwo} - T_{cwi})) - 1/U_c \qquad (9)$$

From equation (9) it can be seen that, the fouling resistance, $R_f$, depends only on the inlet and outlet cooling water temperatures of the test section, for constant surface temperature, fluid properties, fluid flow rate and heat transfer surface area.

A computer program was prepared to calculate the fouling resistance through the three test sections. The input data to the program are the measured inlet and outlet cooling water temperatures, the surface temperature of the test sections, test section dimensions and the mass flow rates. The output of the program is the fouling resistance with time for each velocity.

The fouling curves are presented as a relation between the fouling factor, $R_f$, and time. Figures (3), (4), (5), (6), (7) and (8) illustrate the experimental results for flow velocities of 0.24, 0.35, 0.51, 0.62, 1.21 and 1.42 m/s respectively. From fig.(3), it can be seen that, the fouling resistance appears to be small and has negative values at the first 22 hours. These negative values of $R_f$ are due to the increase in the local heat transfer coefficient as a result of surface roughness caused by the initial particle deposition on the clean surface. In spite of increasing the thermal resistance due to particle deposition, the increase in the film heat transfer coefficient is larger and therefore the fouling factor has a negative value. Also, it can be observed the shape of the saw tooth phenomenon in this figure. This phenomenon is a result of partial removal of some deposits followed by a rapid build up of deposits in a short time. The last 30 hours show that the fouling resistance appears to be approximately constant and the asymptotic fouling resistance is almost obtained ($R^*_f = 0.000777\ m^2.^{\circ}C/W$). The solid curve represents the best fit of the experimental data.

Figure (4) shows the fouling curve for a flow velocity of 0.35 m/s. The fouling resistance in the first 45 hours has a small value and many negative values is observed in the early stages of fouling. During the second 45 hours the fouling resistance was increased slowly with time. A power failure was occurred after 93.5 hours and after that it is observed that the fouling is rapidly increased. This rapid increase in $R_f$ could be due to formation of fouling on another place and transportation of these deposits to the test section. The same power failure occurred with velocities of 0.62 and 1.21 m/s. this phenomenon was also observed in the experimental work of K.E. Coates and J.G. Knudsen [12]. It is seen that the fouling formation has a saw tooth shape due to partial removal of some deposits. This effect is due to sloughing followed by a rapid build up of deposits.

As the fouling layer thickness increases, its thermal resistance increases due to the lower thermal conductivity of the fouling material.

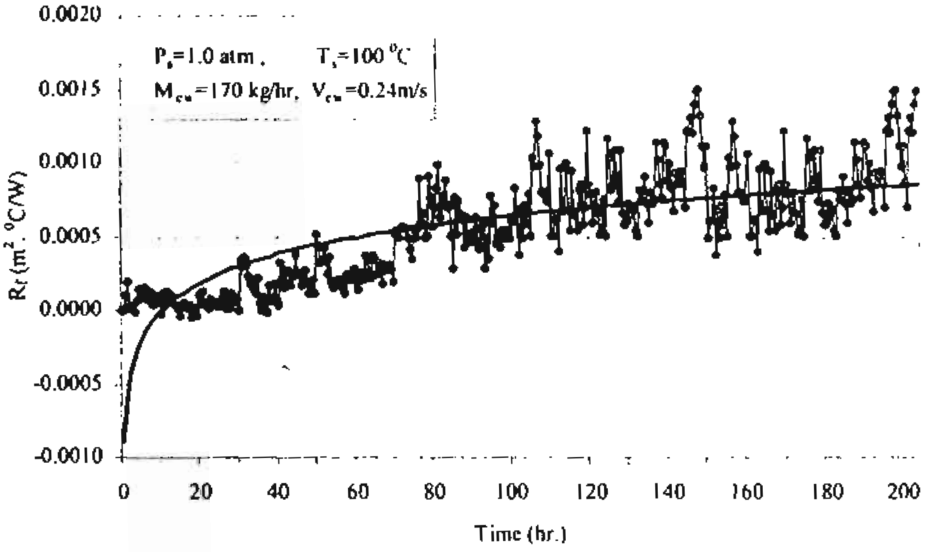


Fig.(3). The fouling factor for a flow velocity of 0.24 m/s

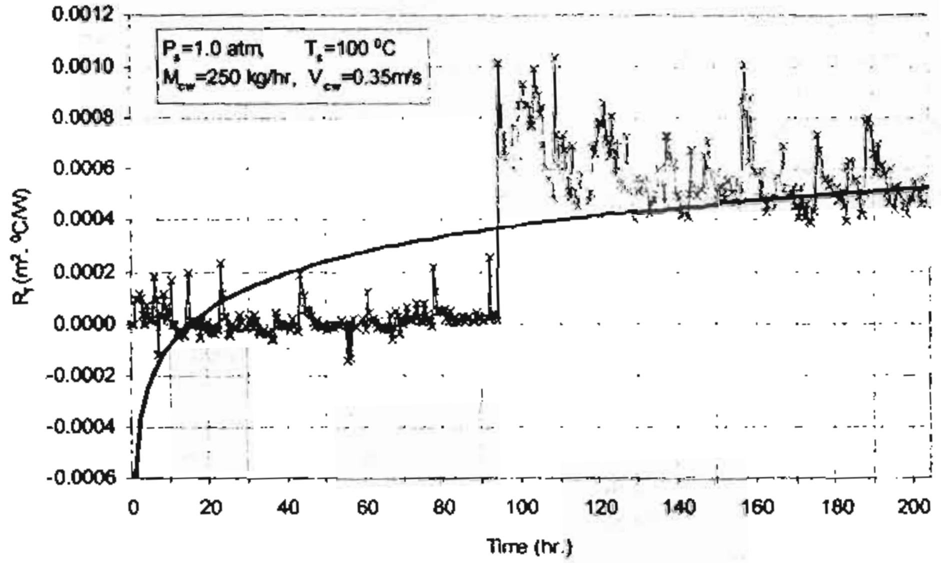


Fig.(4). The fouling factor for a flow velocity of 0.35 m/s

During the last 30 hours the fouling resistance appeared to be constant and the asymptotic resistance, $R^{*}_{f}$ is obtained ($R^{*}_{f}$ = 0.000577 $m^2.°C/W$). The asymptotic resistance of this velocity is less than that of the velocity 0.24 m/s by about 34.95 %.

Figure (5) shows the plot of the fouling factor for a flow velocity of 0.51 m/s. It is seen that, the fouling resistance has the same behavior as the saw tooth effect and it increases gradually with time during the first 160 hours. During the last 40 hours it seems to be constant where the asymptotic fouling resistance is approximately achieved ($R^{*}_{f}$ = 0.000331 $m^2.°C/W$). The asymptotic fouling resistance of this velocity is less than that of velocity 0.24 m/s by about 62.68.

Figure (6) shows the variation of fouling resistance, $R_f$ with respect to time at a flow velocity of 0.62 m/s. It is seen that, the fouling resistance has the same behavior but smaller value than that of the above three velocities due to the higher flow velocity. Also power failure happened after 93 hours of operation and after that the fouling resistance is increased rapidly. During the last 100 hours of operation the fouling resistance is increased by a decreasing rate until the asymptotic resistance is achieved ($R^*_f = 0.000228$ $m^2.°C/W$). This value is less than that of velocity 0.24 m/s by about 74.30%.

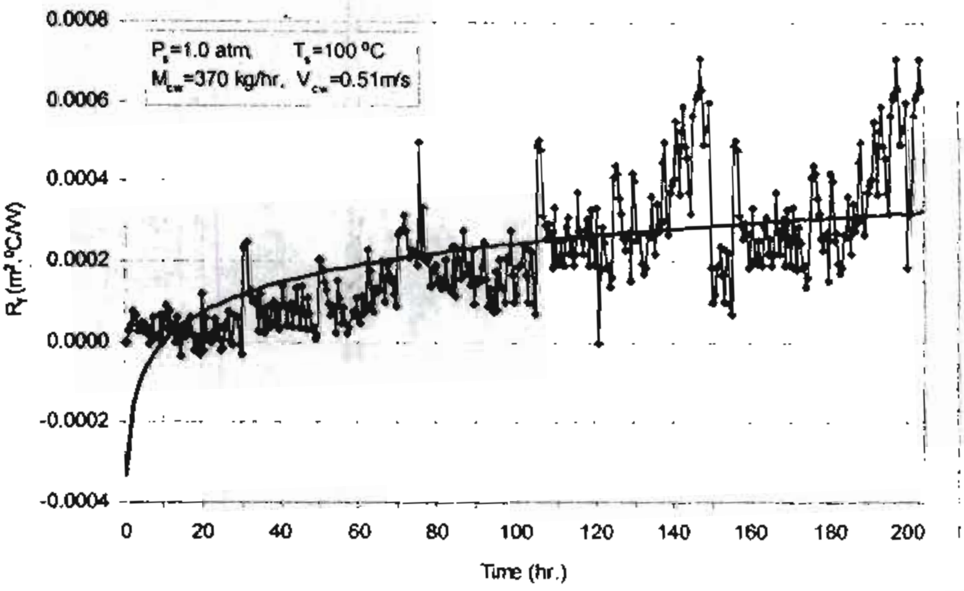


Fig.(5). The fouling factor for a flow velocity of 0.51 m/s

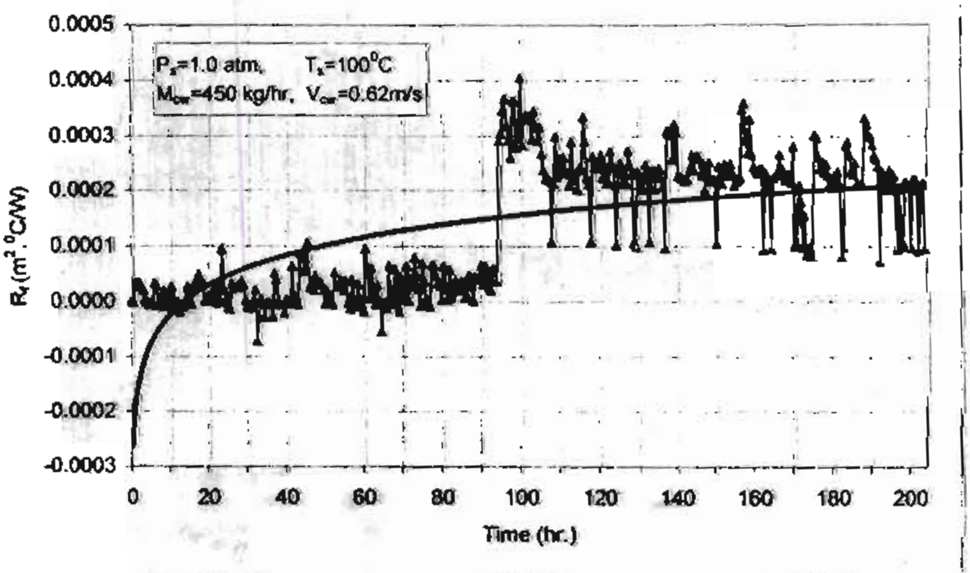


Fig.(6). The fouling factor for a flow velocity of 0.62 m/s

Figures (7) and (8) show the fouling curves for velocities of 1.21 and 1.42 m/s respectively. As shown in both figures, the fouling resistance increases with time and the saw tooth effect appears in both curves. The asymptotic fouling resistance of the velocity 1.21 m/s is achieved after 170 hours of operation ($R^*_f = 0.000146\ m^2.^\circ C/W$). It is smaller than that of flow velocity of 0.24 m/s by about 83.54%, where as the asymptotic fouling resistance of the velocity 1.42 m/s is achieved after 160 hours of operation ($R^*_f = 0.000114\ m^2.^\circ C/W$) and is smaller than that of velocity 0.24 m/s by about 87.16%.

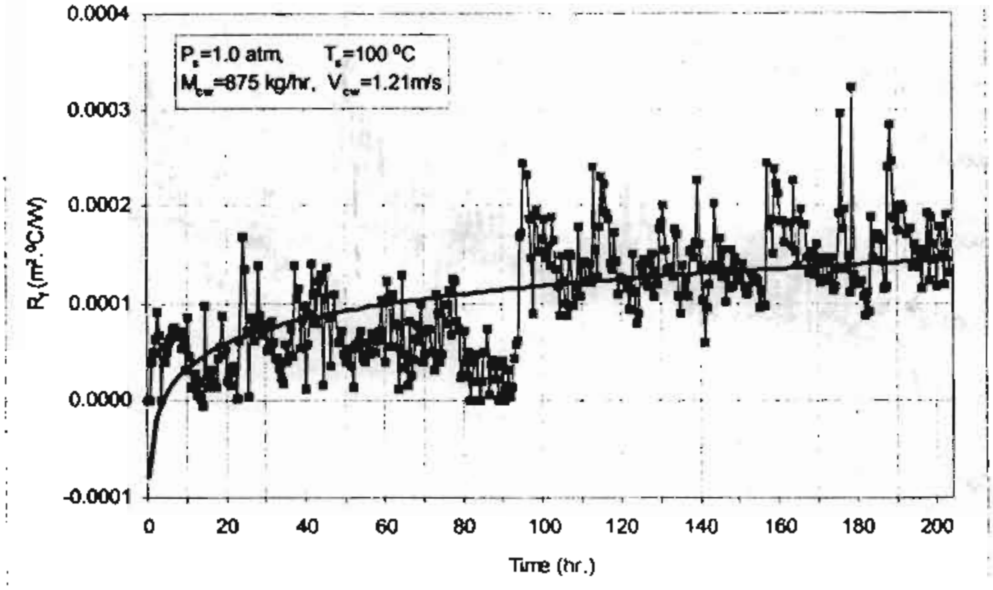


Fig.(7). The fouling factor for a flow velocity of 1.21 m/s

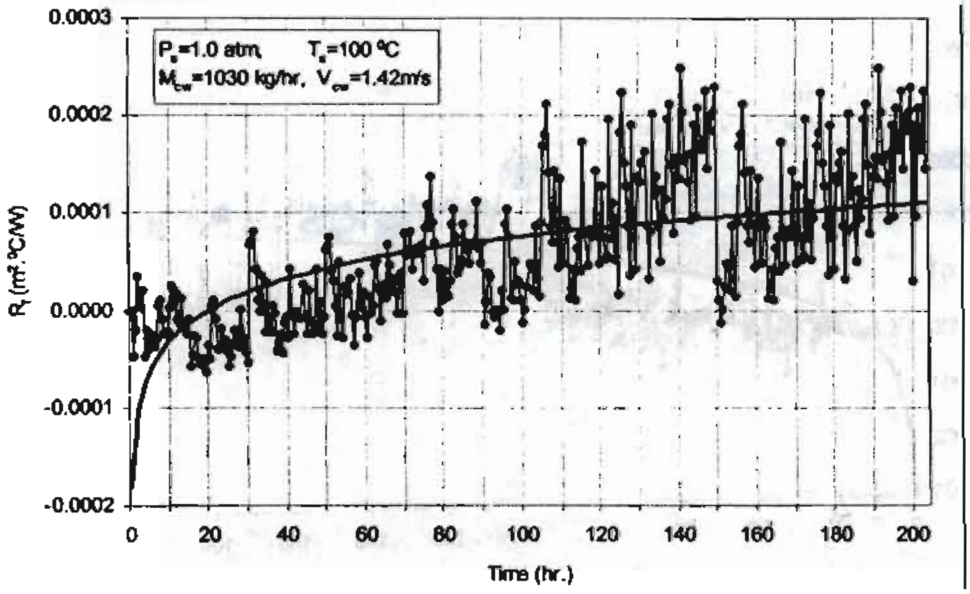


Fig.(8). The fouling factor for a flow velocity of 1.42 m/s

All the obtained fouling curves for the six velocities are plotted in Figure (9) to show the difference between them. From this figure it can be seen that:

- The fouling resistance gradually increases with time in all runs.
- The obtained fouling resistance in this study is of the asymptotic type and the asymptotic values are achieved after about 160 to 180 hours of operation.
- The delay time is almost zero and there is some improvement in the overall heat transfer coefficient at the beginning due to the roughening of the heat transfer surface as a result of odd distribution of deposits on it.
- At the first 25 hrs, the effect of the velocity on the fouling is irregular and after that, both $R_f$ and $R^*_f$ values decrease by increasing the flow velocity.

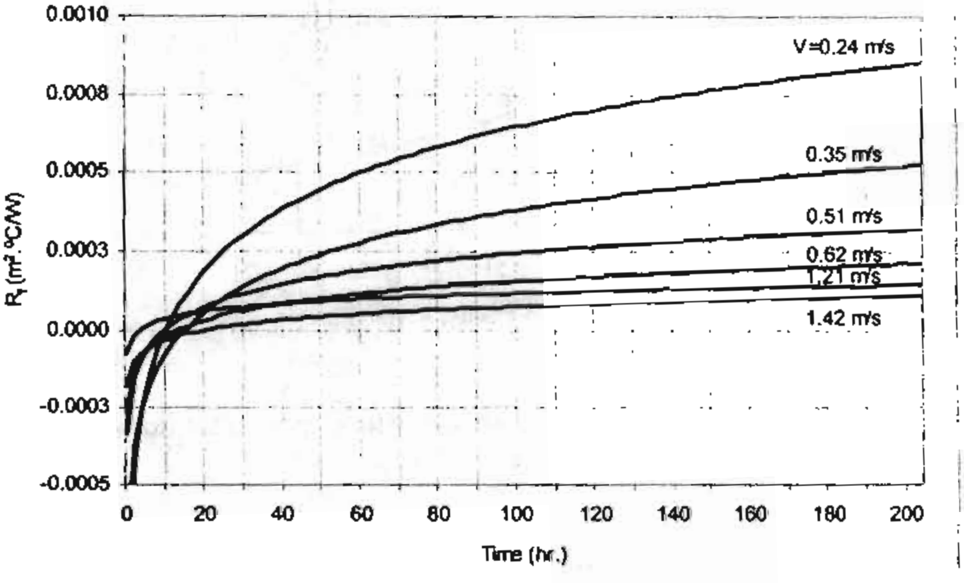


Fig.(9). The fouling factor as a function of time at different flow velocities

The asymptotic fouling resistance is plotted with respect to the flow velocity in Fig.(10). From this figure, the asymptotic fouling resistance decreases as the flow velocity increases under the same operating conditions. At low velocities, the step increase in the flow velocity has a great effect on both fouling and asymptotic fouling resistances but at higher velocities this effect is smaller. The average curve of the asymptotic fouling resistance with the flow velocity (the best fit of experimental data) has the following form:

$$R^*_f = 0.000164/V^{(1.125)} \qquad (10)$$

As mentioned above, the asymptotic fouling resistance mode can be described by an exponential equation as $R_f = R^*_f\,(1-e^{-t/tc})$

From the experimental results for the flow velocity of 0.24 m/s the asymptotic fouling resistance, $R^*_f$, is equal to 0.887 m².°C/kW. Substituting this value in the above equation then;

$$R_f = 0.887\,(1-e^{-t/tc}) \qquad (11)$$

The value of the time constant, $t_c$, can be evaluated from the regression of the fouling curve and using equation

(11). At time t=t$_c$, it is known that $R_f = 0.632R^*_f$, then $R_f(t=t_c)=0.561\ m^2.°C/kW$. Therefore, from the experimental data, at $R_f = 0.561\ m^2.°C/kW$, the value of $t_c = 73.36$ hours, then equation (11) can be rewritten as :

$$R_f = 0.887\ (1 - e^{-0.0136t})\ m^2.°C/kW,$$

where

t in hours

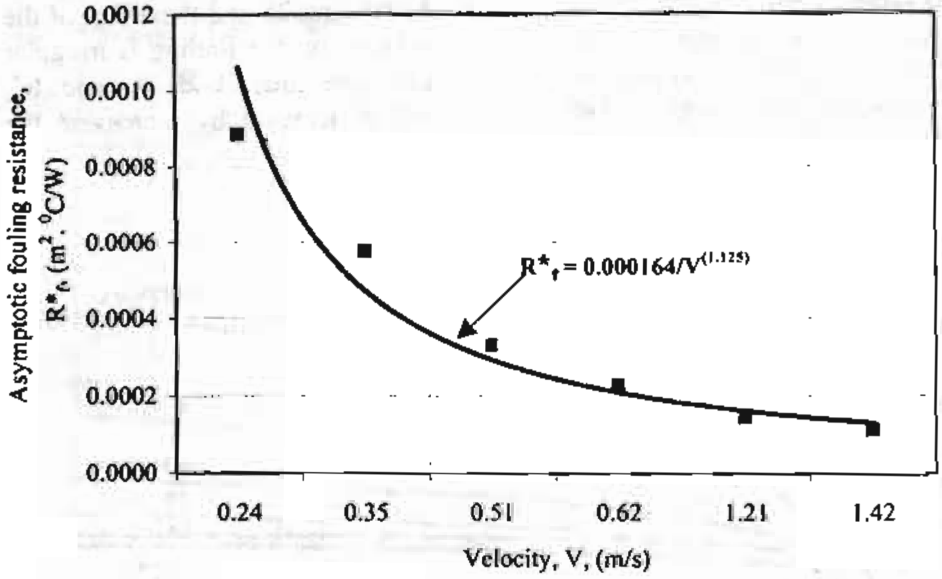


Fig.(10). The asymptotic fouling resistance variation with respect to the flow velocity

For all the tested flow velocities, the asymptotic equation for each velocity can be deduced by using the same above procedure. The asymptotic fouling resistance, the time constant and the reduction in the asymptotic fouling resistance for each tested flow velocity are summarized in table (2).

Table (2) Summary of the experimental results.

| V, *(m/s)* | $R^*_f$, *m². °C/kW* | t$_c$, *hr* | β = 1/ t$_c$, *hr$^{-1}$* | ΔR$^*_f$, % |
|---|---|---|---|---|
| 0.24 | 0.887 | 73.36 | 0.01363 | - |
| 0.35 | 0.577 | 90.73 | 1.01102 | 34.95 |
| 0.51 | 0.331 | 73.32 | 0.1364 | 62.68 |
| 0.62 | 0.228 | 87.85 | 0.01138 | 74.30 |
| 1.21 | 0.146 | 43.95 | 0.02278 | 83.54 |
| 1.42 | 0.114 | 99.12 | 0.01009 | 87.16 |

## Conclusions and Recommendations

The experimental runs show that, at the first 25 hrs the effect of the velocity on the fouling is irregular after that both $R_f$ and $R^*_f$ values decrease by increasing the flow velocity. The delay time is almost zero and there are some improvements in the overall heat transfer coefficient at the beginning due to the roughening of the heat transfer surface as a result of odd distribution of deposits on it. The saw tooth effect is observed in all runs and the fouling resistance gradually increases with time. The obtained fouling resistance in this study is of the asymptotic type and the asymptotic values are achieved after about 160 : 180 hours of operation. The asymptotic fouling resistance is decreased by 34.95% when the flow velocity is increased from 0.24 to 0.35 m/s while it is decreased by 21.92% when the flow velocity is increased from 1.21 to 1.42 m/s. This means that, at low velocities, the fouling resistance is affected by the change of flow velocity more than at high velocities.

In the design and operation of heat transfer equipment, the flow velocities must be as high as possible. A theoretical investigation of this problem is essential. A future work with other fouling fluids and other operating parameters is recommended.

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