

Research Article

The Effect of Circulating Glass Beads on Crystallization Fouling and Fouling Resistance in Double-Pipe Heat Exchanger

Vinous M. Hameed †, Fadya F. Mohammed* and Basim O. Hasan ‡

†Mechanical Engineering Department, College of Engineering, Al-Nahrain University, Iraq

‡Chemical Engineering Department, College of Engineering, Al-Nahrain University, Iraq

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Abstract

Crystallization fouling experiments were performed for double pipe heat exchanger under counter flow condition in which sodium sulfate (Na_2SO_4) at saturation condition and constant bulk temperature of ($40^\circ C$) were made to flow in the shell at different Reynolds number ($Re_h = 5000 - 12000$), cold water flowing in the pipe at constant temperature of ($12^\circ C$) at different Reynolds numbers ($Re_c = 11000 - 37000$). The overall heat transfer coefficient and fouling resistance were determined from the measurement of the inlet and outlet temperature of the system at the given different velocities. Glass beads ($3mm \varnothing$) at two different concentrations ($1.25 - 0.625 g/l$) were introduced to the salt solution to minimize the effect of fouling. The experimental results showed that the circulation of glass beads in the heat exchanger annulus results in higher heat transfer rates than the case where no fouling is present. The enhancing effect of glass beads on heat transfer is more pronounced at lower velocities and lower concentration. Fouling curves for glass beads circulation at both concentrations show a drop in the values of fouling resistance due to the continuous removal of the crystalline layer by the glass beads.

Keywords: Crystallization fouling, Heat Exchanger, Heat transfer coefficient, Fouling Resistance, Glass bead.

1. Introduction

A heat exchanger is a heat-transfer device that is used for transfer of internal thermal energy between two or more fluids available at different temperatures. In most heat exchangers, the fluids are separated by a heat-transfer surface, and ideally, they do not mix. Common examples of heat exchangers used in daily life are automobile radiators, air conditioning, and oil coolers (Kuppan, 2000). After a period of operation, undesired materials begin to accumulate on the heat exchanger surface. The undesirable material may be crystals, sediments, polymers, coking products, inorganic salts, biological growth, and corrosion products. This process is referred to as fouling; in general, fouling results in a reduction in thermal performance, an increase in pressure drop, may promote corrosion, and may result in eventual failures of some heat exchangers (Ramesh and Dušan, 2003). The accumulation of unwanted deposits on the surfaces of heat exchangers is usually referred to as fouling. Crystallization fouling which is the formation of crystals on the heat exchanger surfaces is a common type of fouling in the aqueous systems, for example, system using water for cooling purposes or evaporative desalination (Bott, 1995). The accumulation of these deposits is a function of the

surface temperature, material and condition, fluid velocity, flow geometry and fluid composition (Syed *et al.*, 1992).

Fouling is generally expressed in terms of fouling factor or fouling resistance (R_f) which must be included along with the other thermal resistances making up the overall heat-transfer coefficient. Fouling factors must be obtained experimentally by determining the values of U for both clean and dirty conditions in the heat exchanger. The fouling factor is thus defined as (Holman, 2010):

$$R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}} \quad (1)$$

Fouling curves represent the relation between the thermal resistances of the crystalline deposits and the time. These curves can have different trends depending on the process parameters and the dominant fouling mechanism, where the fouling rate can either be constant or decrease with time. Fig.1 illustrates these possible trends. In Fig.1 t_d represents the delay period for new or clean heat exchanger where no deposition occurs and high initial heat transfer coefficient remain unchanged for a certain period of time (Hans Müller-Steinhagen, 1999).

*Corresponding author: Fadya F. Mohammed

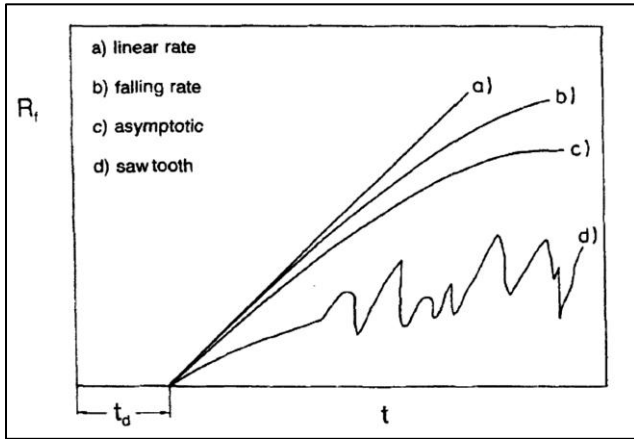


Fig.1 Possible fouling resistance curves versus time (Hans Müller-Steinhagen, 1999).

Factors effecting fouling can be classified into three categories: operating parameters, heat exchanger design characteristic, and solution properties. Flow velocity has a complex effect on fouling; an increase in flow velocity may either increase the fouling rate if the mass transfer is the controlling step or decreases if the interfacial shear has the greatest effect where the deposition rate is reaction controlled (Bott, 1997).

In their study (Hasson *et al.*, 1968) found that CaCO_3 deposition in turbulent, constant heat flux conditions at annular test section, with unfiltered, supersaturated tap water is controlled by the diffusion mechanism in which fouling rate increases with an increasing Reynolds number at the constant surface temperature. While (Hasson and Zahavi, 1970) investigate CaSO_4 scale deposition in an annular heat exchanger shows that scale-layer growth decreases with increasing flow velocity; similar effect of increasing flow velocity was observed by (Bansal and Müller-Steinhagen, 1993) for crystallization fouling of CaSO_4 in a plate heat exchanger. An agreement to this finding was proved by (Mwaba *et al.*, 2006a) and (Mwaba *et al.*, 2006b) where the induction period is reduced by increasing the flow velocity and the rate of growth decreased by about 20% for higher Reynolds number. Fouling mechanism changing from diffusion control at lower velocities to reaction control as velocity increases was observed by (Najibi *et al.*, 1997) for crystallization fouling of CaCO_3 during subcooled flow boiling where heat is transferred by forced convective heat transfer. Such behavior was also noticed by (Helalizadeh *et al.*, 2000) for fouling process of mixed salts solution of CaCO_3 - CaSO_4 in an annular duct being diffusion control at low velocity changing into reaction control with the increase of flow velocity. This conclusion was also proposed by (Fahiminia *et al.*, 2007) for crystallization fouling of CaSO_4 shows a shift in the mechanism of fouling rate control with increasing velocity from diffusion control to surface integration with increasing fluid velocity.

An experimental study conducted by (Zhenhua *et al.*, 2008) to investigate the fouling process of calcium

carbonate on the heat transfer surface during forced convective heat transfer. The heat transfer test section is composed of two concentric tubes. Different factors including fluid velocity, hardness, alkalinity, solution temperature, and wall temperature under were the fouling behavior was monitored. Asymptotic fouling curves varying with time were obtained. With the fluid velocity decreasing, hardness and alkalinity increasing, and solution temperature and heat transfer surface temperature increasing the fouling rate and asymptotic fouling resistance increased and the induction periods were shortened. The components of fouling that formed on the heat transfer surface included crystallization fouling and particulate fouling.

The fouling behavior of saturated solution of CaSO_4 was investigated by (Albert *et al.*, 2009) in double pipe heat exchanger with electro-polished tube as well as with common stainless steel tube under a fixed condition with Reynolds number of 18000 corresponding to flow velocity of 0.65 m/s. The results show the significance to consider both the hydrodynamic and heat balance to describe the fouling process.

The effect of hydrodynamics on crystallization fouling of saturated sodium sulfate (Na_2SO_4) over a pipe containing cold water under cross flow condition was investigated by (Hasan *et al.*, 2012) , the experimental results showed that increasing the hot solution (salt solution) velocity decreases the fouling thermal resistance, while increasing the cold water velocity decreases the fouling thermal resistance, but at the same time it increases the fouling layer thickness; the crystallization process were found to be under activation control (i.e. chemical kinetic control) so that the mass transport of salt plays only a minor role. Therefore the controlling mechanism of fouling varies depending on the considered system.

Fouling mitigation techniques have long been investigated. Efforts have been made either to minimize the potential of a fluid to form deposits or to be more effective in removing of deposits. In their review (Müller-Steinhagen *et al.*, 2011) categorized the main fouling mitigation strategies as; first through proper design of heat exchanger, second by on-line mitigation method and the least favorable method is the off-line cleaning of heat exchanger which requires the shut-down of the system. In fact, a combination of these methods may be required to mitigate fouling.

Self-cleaning heat exchangers are a very effective technology to reduce or even eliminate scale formation in many types of applications. Particles of different materials and shapes are transported upward through the vertical heat exchanger tubes together with the fouling liquid (Klaren *et al.*, 2007). They are then separated from the liquid and returned in an external downcomer. In addition to having a slightly abrasive effect on the heat transfer surface, the particles will also improve the tube-side heat transfer coefficients. Typical applications include desalination, processing of aqueous solutions and processing of hydrocarbons.

In their study, (Kim *et al.*, 1996) investigated the effect of glass beads (3mm \emptyset) circulating through heat exchanger on the heat transfer coefficient and fouling characteristic of the flow, the experimental results showed that the glass particles enhanced the heat transfer at the flow velocities lower than 1.0 m/s; this enhancement is related to the collision frequency by the particles on the tube wall, below this velocity the heat transfer coefficient increases slightly as the particle volume fraction increases, and is almost constant independent of the flow velocity, also fouling experiments shows that the glass particles efficiently removed the pre-existing ferric oxide deposits as well as hindered further deposits build up.

Further investigation on the enhancing effect circulating particles was done by (Kim and Lee, 2001) they studied the effect of different glass beads diameter (1.5 mm \emptyset , 3 mm \emptyset , 4 mm \emptyset) at a fixed volume fraction on heat transfer coefficient, the results showed that as the particles diameter increases the heat transfer coefficient increases.

In their experimental study, (Kang *et al.*, 2011) investigated the effect of variety of solid particles at different sizes, circulating through a vertical shell and tube heat exchanger, on the heat transfer coefficient; they conducted that the increase in heat transfer coefficient was in order of sand, copper, steel, aluminum, and glass this behavior might be associated with the parameters such as surface roughness or particle heat capacity; also a higher heat transfer coefficient was noticed for particles with the diameter of 2.5 and 3 mm \emptyset compare to 2 mm \emptyset diameter particles at lower velocity, this is could be related to the fact that the particles of 2.5 and 3 mm \emptyset become closer to spherical geometries, the geometries increase the fluid resistances on account of higher projected areas of solid particles resulting in higher hitting frequencies of solid particles to the surfaces.

The aim of this work is to investigate the effect crystallization fouling on the efficiency of heat transfer in shell and tube heat exchanger. Effect of crystallization fouling in the shell side of the heat exchanger was studied under different operating conditions (flow velocity and time). In addition, the present work aims to mitigate the crystallization fouling using glass beads when added to the flow of hot fluid to reduce the effect of deposits on the heat transfer rate. The effect of concentration of glass particles on the mitigation process was also investigated.

2. Material and Method

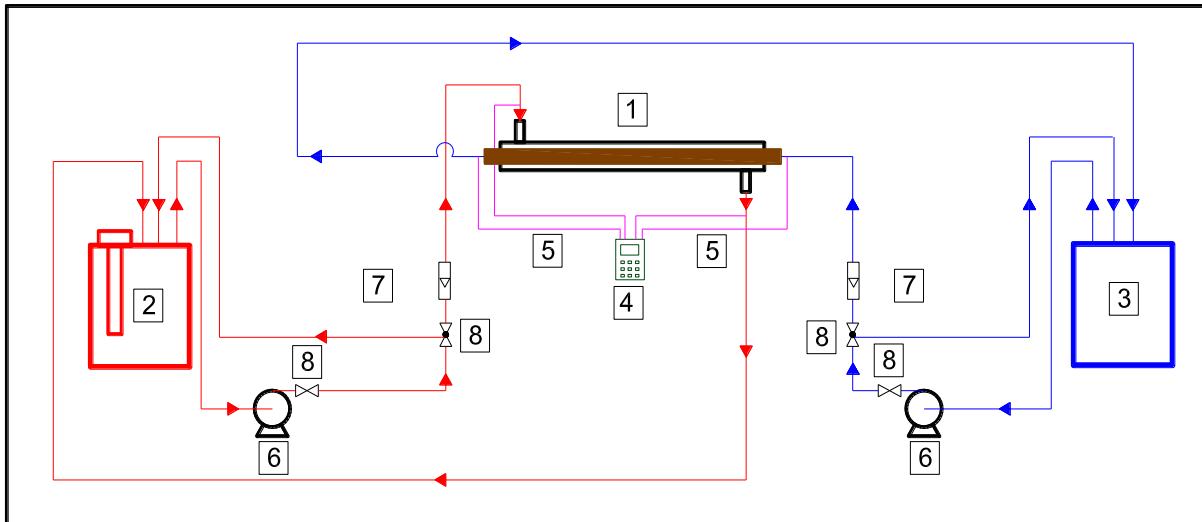
The experimental apparatus as shown in detail in Fig.2 consist of double pipe heat exchanger was constructed for the experimental investigation. Stainless steel shell with inner diameter $D_{is} = 28$ mm, outer diameter $D_{os} = 31.08$ mm and length of 1500mm, the inside tube material is copper with inside diameter $D_{it} = 15$ mm, outside diameter $D_{ot} = 16$ mm and length of 1820 mm.

A counter flow condition was maintained for all sets of experiments, where the hot fluid flow in the annulus and cold fluid flow in the inside tube. To minimize the possible loss in heat the outer shell of the heat exchanger was warped with insulation.

A rectangular tank made of Perspex of dimensions 600 \times 600 \times 400 mm to service as hot fluid resource equipped with a heater. The tank was filled with tap water where it was heated to the desired temperature before being pumped into the test section. The salt solution replaces the tap water in the tank later and also pumped into the test section. Chiller with a tank capacity of 220 liters was used to provide cold fluid to the test section, the tank was filled with tap water and set to cool and maintain the water temperature at 12 $^{\circ}$ C before being pumped to the heat exchanger.

Two centrifugal pumps were installed and connected to the experiment apparatus to pump the hot and cold fluid from their reservoirs into the heat exchanger. Each pump has a capacity of $Q_{max} = 103$ l/min and $H_{max} = 26$ m. Both fluid flows were controlled by two calibrated rotameters. The rotameters were calibrated at each operating temperature. The flow rate through the test section was controlled by four valves made of PVC. One valve was placed in the entrance of the hot test section before the rotameter of the hot fluid to control and adjust the test section flow rate. Another valve was placed in the by-pass line to help in obtaining the desired flow rate in the test section and to circulate the hot fluid to get the desired temperature (40 $^{\circ}$ C). Another valve was placed in the entrance of the cold test section before the rotameter of the cold water to control and adjust the test section flow rate. The last valve was placed in the by-pass line to help in obtaining the desired flow rate through the test section and to circulate the cold water for obtaining the constant temperature of 12 $^{\circ}$ C. Different sizes of rubber tubes and fitting were used to connect the parts of apparatus. For monitoring fouling inside the tube, four k-type thermocouples were connected to the data logger at one end while the other end was installed at the inlets and outlets of both cold and hot fluid at distances of 30 mm from each pipe end.

The thermocouples were calibrated using cold water of known temperature and found to have $\pm 0.1^{\circ}$ C accuracy. Ninety liters of tap water was used to fill the hot fluid tank, 220 liters of water used in the chiller. The first sets of experiments were to study the overall heat transfer coefficient in the clean condition, i.e., without the presence of fouling. The hot water was first introduced into the annulus at three different values of Reynolds numbers 5000, 10000 and 12000, cold water flows into the inner tube at Reynolds numbers 11000, 20000, 30000 and 37000. The temperature of hot fluid was 32 $^{\circ}$ C with the cold fluid temperature was maintained at 12 $^{\circ}$ C.



1- Double pipe heat exchanger, 2- Hot fluid tank, 3- Cold water tank (Chiller), 4- Data logger (Temperature recorder), 5- Thermocouples, 6- Pumps, 7- Rotameters, 8- Valves.

Fig.2 Schematic diagram of experimental apparatus

The second sets of experimenters were to study the effect of crystallization fouling on the performance of heat exchanger. The hot fluid tank was filled sodium sulfate (Na_2SO_4) the solubility of sodium sulfate in water rises more than tenfold between 0 °C to 32.384 °C, where it reaches a maximum of 49.7 g/100 g of water, as shown in Fig.3, at this point the solubility curve changes slope, and the solubility becomes almost independent of temperature (Linke and Seidell, 1965).

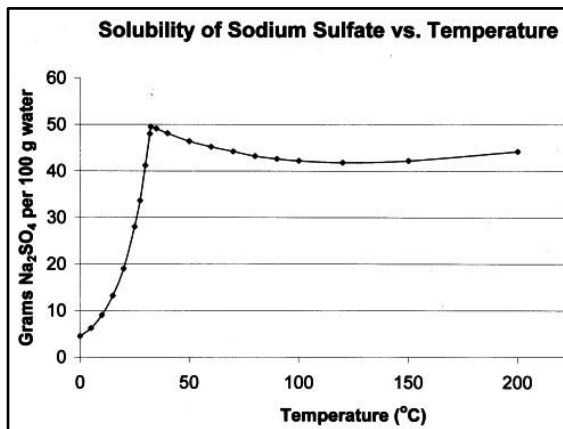


Fig.3 Solubility of sodium sulfate as a function of temperature (Linke and Seidell, 1965).

At the start of each experiment, the heater and chiller were set at the required temperature. Then the control valve was opened and the pump started to flow the hot water through the rotameter and, the outer tube of the double pipe heat exchanger. The cold water from the chilled water unit was allowed to enter the inner tube of heat exchanger via a flow control valve after flowing through the pump and rotameter. When the cold water enters the wall starts to cool leading to bring up the salt in the hot solution to the supersaturation

conditions and, hence, the crystallization fouling occurs because salt is of normal solubility leading to the growth of crystalline layer. Temperatures of four points two at the inlet and two at the outlet of each fluid were recorded from the start of heat transfer process between the two fluids. The temperature reader was set to record the data every five seconds.

An on-line physical mitigation technique was used to combat the crystallization fouling effect. Glass beads (3mm ϕ) as shown in Fig.4 were introduced to the salt solution at two different concentrations (0.625 g/l - 1.25 g/l) and its effect on heat transfer and crystallization fouling was investigated. Each experiment was carried out at least twice. The reproducibility of the results was in $\pm 5\%$.

Although the heat exchanger was covered by rubber insulation, a difference between heat duty of cold and hot fluids of about 3% to 8% was noticed due to convection and radiation heat losses from the test section to surroundings. The same observation was noticed in previous work (Arun *et al.*, 2013).

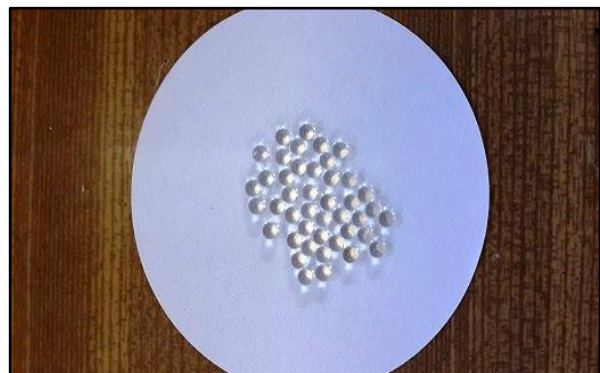


Fig.4 Glass beads used in the test section

3. Data Processing

The experimental data were used to calculate overall heat transfer coefficient, the heat transfer rate of the hot and cold fluid can be expressed as:

$$q_h = m_h \cdot C_{ph} (T_{hi} - T_{ho}) \tag{2}$$

$$q_c = m_c \cdot C_{pc} (T_{co} - T_{ci}) \tag{3}$$

Where q_h , q_c , m_h , m_c , C_{ph} and C_{pc} are the heat transfer rates, the mass flow rates, and the heat capacities of the hot and cold fluid respectively. T_{hi}, T_{ci}, T_{ho} and T_{co} are the inlet and outlet temperatures of the hot and cold fluids.

The overall heat transfer coefficient based on the outer diameter of the inside tube (U_o) is calculated from the following relation:

$$U_o = \frac{q}{A_o \Delta T_{LMDT}} \tag{4}$$

where $A_o = \pi D_{ot} L$ the heat transfer area based on the outer diameter of the inside tube, where $L = 1.5$ m and $D_{ot} = 16$ mm.

For the counter flow condition the expression representing the log mean temperature difference will be:

$$\Delta T_{LMDT} = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln \left(\frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}} \right)} \tag{5}$$

Reynolds number is based on the different flow rate at the inlet of the test section.

$$Re = \frac{\rho u D}{\mu} \tag{6}$$

The diameter for the case of fluid flowing in the inside tube flow will be $D_{it} = 15$ mm, as for annulus flow case the hydraulic diameter will be used:

$$D_H = D_{is} - D_{ot} \tag{7}$$

which well equal to $D_H = 28 - 16 = 12$ mm.

3. Results and Discussion

Effect of crystallization fouling of Na_2SO_4 salt presence in the hot water as if flows in the annulus on the overall heat transfer coefficient is illustrated in Fig.5, Fig.6, and Fig.7. The results show a reduction in the overall heat transfer coefficients by percentage of 45%~20% depending on Re_h due to the formation of the crystalline layer at the outer surface of the inside tube where the cold water flows. As the saturated hot solution of Na_2SO_4 come to contact with the cold surface it forms a thin layer of crystals (since this salt is of a normal solubility which is more soluble at higher temperatures) this layer of crystal represents additional resistance to heat transfer due to its low thermal conductivity. A steady increase in the values of the overall heat transfer coefficients with the increase in Re_c values is evident in Fig.5, Fig.6 and Fig.7 despite of salt deposition, this due to the fact that as the velocity of the cold water increase the temperature of

the outer surface of the inside tube is decreased enhancing more salt to deposit and the crystalline layer to be thicker. Simultaneously the considerable decrease of the surface temperature leads to an increase in the overall heat transfer coefficient. These findings agree with the previous studies of (Hasan et al., 2012).

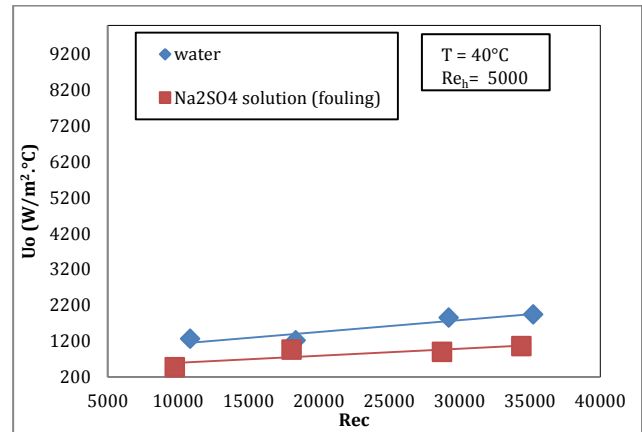


Fig.5 Variation of U_o with Re_c at constant temperature $T = 40^\circ C$ and $Re_h = 5000$, (Fouled Condition)

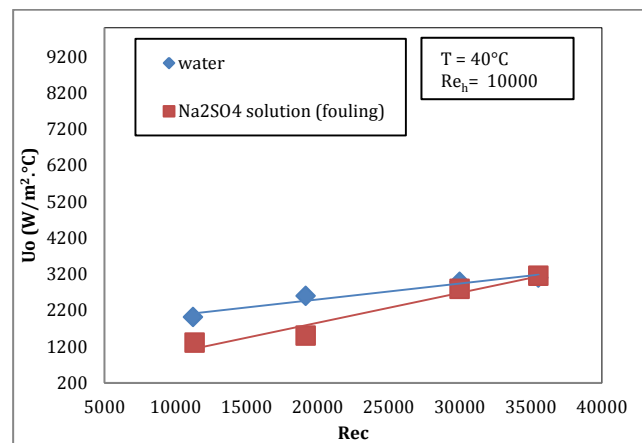


Fig.6 Variation of U_o with Re_c at constant temperature $T = 40^\circ C$ and $Re_h = 10000$, (Fouled Condition).

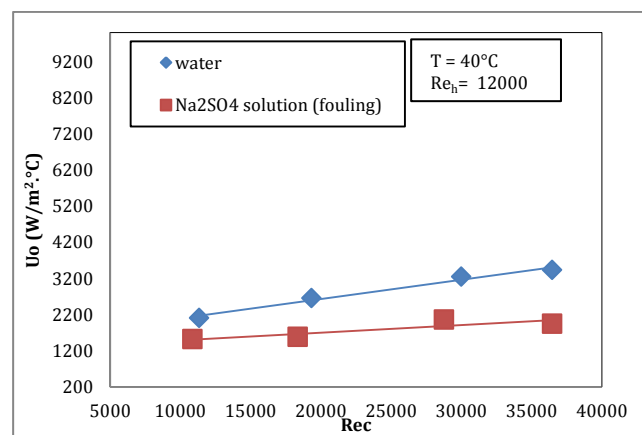


Fig.7 Variation of U_o with Re_c at constant temperature $T = 40^\circ C$ and $Re_h = 12000$, (Fouled Condition).

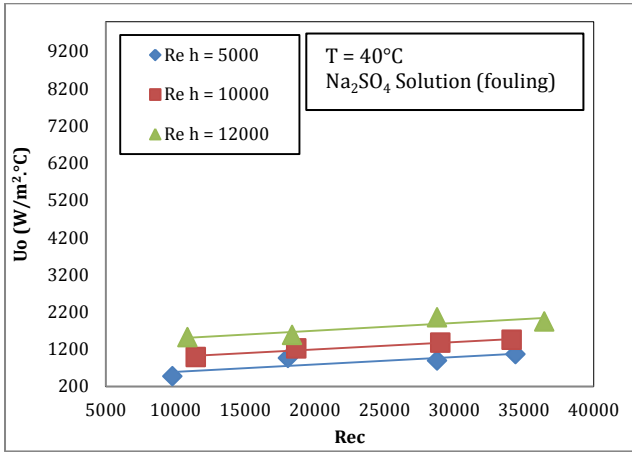


Fig.8 Variation of U_o with Re_c at different Re_h values and constant temperature $T = 40^\circ\text{C}$, (Fouled Condition)

Fig.8 represents the effect of different values of Re_h on the overall heat transfer coefficient at constant temperature $T=40^\circ\text{C}$ with the presence of fouling. An increase in Re_h leads to an increase in the overall heat transfer coefficient. This is also referred to the decrease in the thickness of the thermal sublayer that accompanies the increase in the velocity of hot water flowing in the annulus which represents a resistance to heat transfer. A similar effect of increasing flow velocity was observed by (Hasson and Zahavi, 1970) and (Fahiminia et al., 2007).

To minimize the effect of crystallization fouling of Na_2SO_4 salt on the heat transfer process, glass beads (3mm \varnothing) were introduced into the salt solution at two different concentrations (1.25 g/l - 0.625 g/l) as it flows in shell side. Fig.9, Fig.10, and Fig.11 shows the effect of glass beads addition on the overall heat transfer coefficient values at constant temperature $T=40^\circ\text{C}$ and three different values of Re_h with varying in Re_c where M represents the concentration of glass beads in the salt solution. Significant increase in the values of the values of the overall heat transfer coefficients is noticeable. The percentage increase in the overall heat transfer coefficients is 16%~400% for glass beads concentration (1.25 g/l), whereas, for (0.625 g/l) it was 12%~740%.

Such behavior was also monitored in previous studies including (Kim et al., 1996), (Kim and Lee, 2001), and most recently (Kang et al., 2011). They all attributed this behavior to the continued removal of foulant layer by the solid particles as they continuously hit the heat transfer wall reducing its effect on the overall heat transfer coefficient the frequency at which one particle hit the heat transfer wall is referred to as "hitting frequency". As the glass beads hit the wall it does not only remove the foulant layer but also disturb the laminar sublayer that present near wall the heat transfer in turbulent flow condition which represent the main resistance to heat transfer, reducing it effect and enhancing the heat transfer.

It can be seen from Fig.9 and Fig.11 that at lower concentration (0.625 g/l) of the glass beads in the

foulant solution gives greater enhancement compares to the higher concentration (1.25 g/l), it is speculated that the glass beads can move more freely in the annulus of the heat exchanger at that lower concentration and the hitting frequency become more rapid leading to more cleaning action and disturbance to the laminar sublayer giving a better heat transfer rate.

The variation of overall heat transfer coefficient with Re_c at different values of Re_h at the two concentrations of glass beads is represented in Fig.12 and Fig.13. The result shows that the enhancing effect of glass beads is more pronounced at lower velocities. In their investigation (Kim and Lee, 2001) and (Kang et al., 2011) observed the same decrease in the values of the overall heat transfer coefficients as the flow velocity increases; (Kim and Lee, 2001) and (Kang et al., 2011) associated this behavior with an increase in the hitting frequency and thus increase the overall heat transfer coefficient.

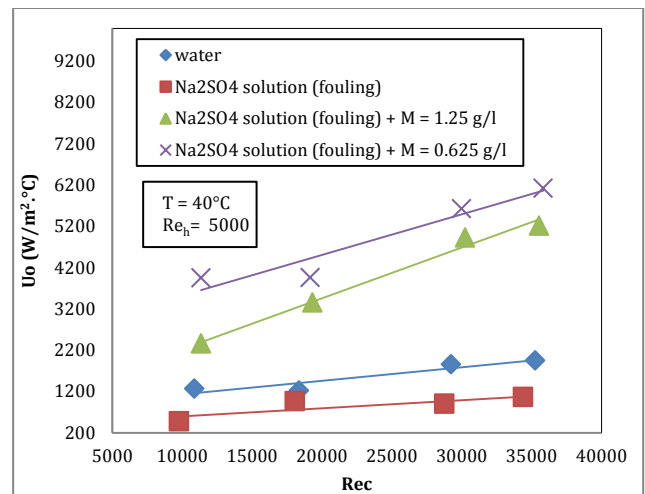


Fig.9 Variation of U_o with Re_c at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 5000$, (Presence of glass beads).

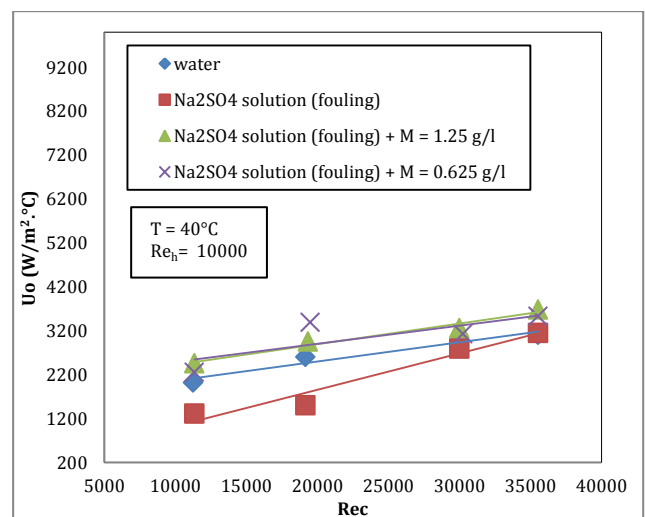


Fig.10 Variation of U_o with Re_c at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 10000$, (Presence of glass beads)

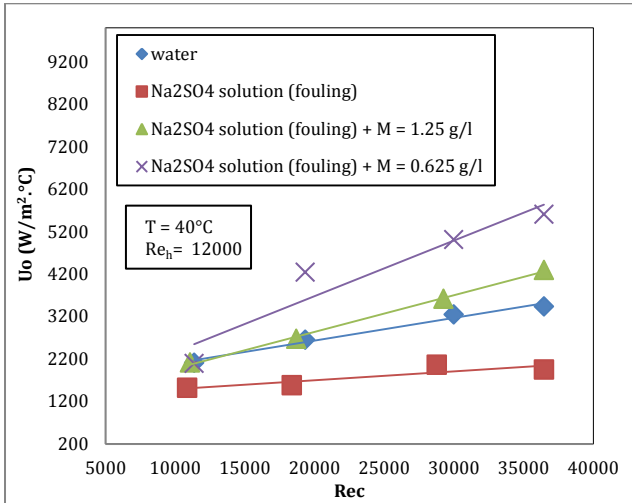


Fig.11 Variation of U_o with Re_c at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 12000$, (Presence of glass beads).

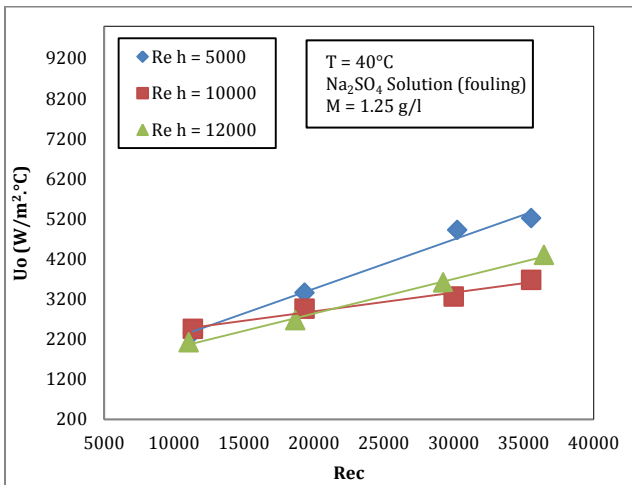


Fig.12 Variation of U_o with Re_c at different Re_h values and constant temperature $T = 40^\circ\text{C}$, (Presence of glass beads $M = 1.25 \text{ g/l}$)

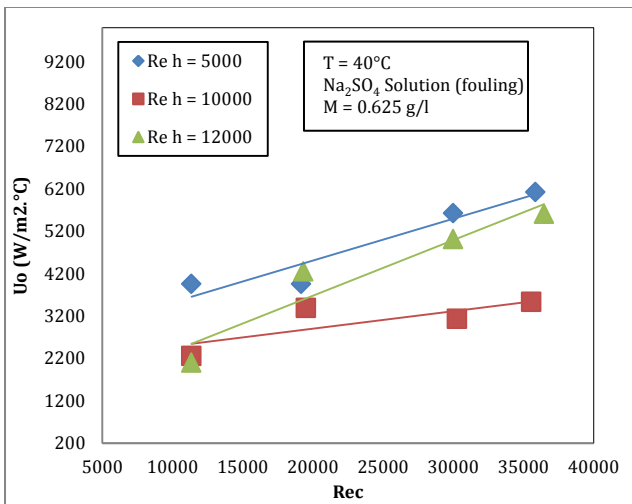


Fig.13 Variation of U_o with Re_c at different Re_h values and constant temperature $T = 40^\circ\text{C}$, (Presence of glass beads $M = 0.625 \text{ g/l}$)

Fouling curves represent the relation between the thermal resistances of the crystalline deposits and the time. The fouling resistances were calculated from the heat transfer coefficients at the beginning of each experiment and the actual heat transfer coefficients after a creation operational period according to Eq. (1). The dashed lines in the figures represent the best fit for the curves under logarithmic function; such method in representing the best fit for the data had been noticed in literature (Mostafa *et al.*, 2007a), and (Mostafa *et al.*, 2007b).

In Fig.14 the variation of thermal resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 5000$ at two different Re_c values is illustrated. It shows that as Re_c value increases from 10000 to 37000 the thermal resistance decrease, due to the decrease in the temperature of the outer surface of the inside tube and thus the heat transfer rate increases leading to a decrease in thermal resistance values. It is evident that the fouling resistance increases asymptotically with time, which is in accordance with previous studies of crystallization fouling and this agreed with (Helalizadeh *et al.*, 2000), (Mwaba *et al.*, 2006b), (Mostafa *et al.*, 2007b), and (Hasan *et al.*, 2012). Asymptotic fouling behavior, represented by the fit dashed line, is noticed for $Re_c = 10000$ changing to linear behavior as the velocity increases to $Re_c = 37000$.

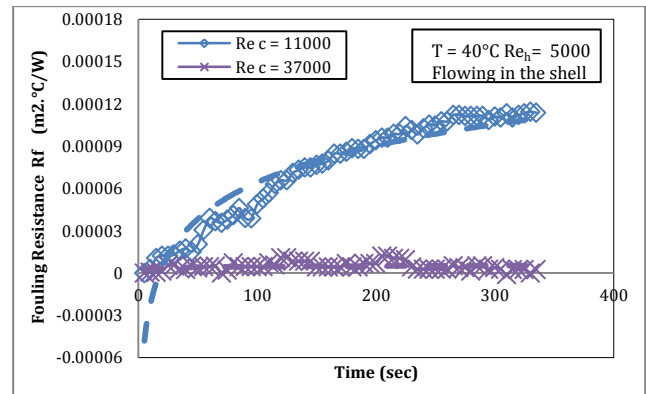


Fig.14 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 5000$ for different Re_c values

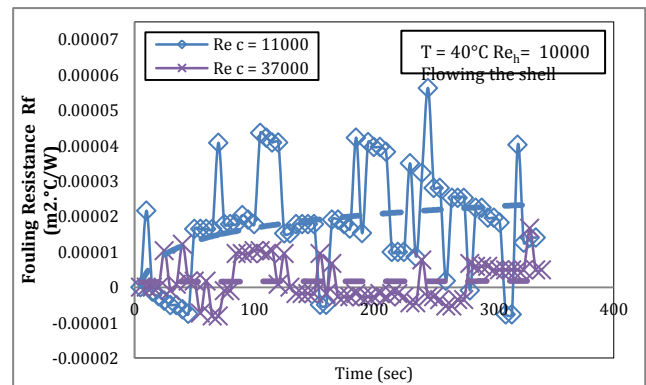


Fig.15 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 10000$ for different Re_c

In Fig.15 the shape of sawtooth phenomena is noticed for the curves. This might be attributed to the partial removal of crystalline deposited followed by rapid buildup of deposits in short intervals of time (Mostafa et al., 2007b). The asymptotic and linear behavior of fouling resistance is still evident for $Re_c = 11000$ and $Re_c = 37000$ respectively.

Asymptotic trend curves is characteristic of soft or fragile deposits which tear off easily due to the shear force of the flow, while the linear trend curves indicates that the deposition rate is either constant and there is no removal, or that the difference between deposition rate and removal rate is constant (Helalizadeh et al., 2000).

Many studies have been made to investigate the effect of velocity on the fouling rate. (Hatch, 1973; Zahid and Konstantinos, 2015) and (Hasson et al., 1968) stated that increasing flow velocity of the foulant solution increases fouling rate. While (Hasson and Zahavi, 1970) and (Bansal and Müller-Steinhagen, 1993) results showed a decrease in fouling rate as the velocity increases. The velocity effect depends on the mechanism that governs the fouling process either mass control or surface action control or a combination of both (Bansal et al., 2008). In Fig.15 and Fig.16 as the velocity of hot foulant solution increases to $Re_h = 10000$ and $Re_h = 12000$ respectively, the values of fouling resistance drops compare to the values in Fig.14 at $Re_h = 5000$. This due to the fact that as the velocity of the hot solution increases the mechanism of fouling changes from mass transfer control to reaction or surface temperature control. Meaning that at low velocity the thickness of the mass transfer boundary layer is thick and molecular diffusion has some effect on the fouling rate, however, as the velocity increases the thickness of the boundary layer decreases and mass transfer across it is no longer affects the fouling rate and the fouling mechanism changes to surface temperature control. These results agree with previous findings of (Helalizadeh et al., 2000) and (Fahiminia et al., 2007).

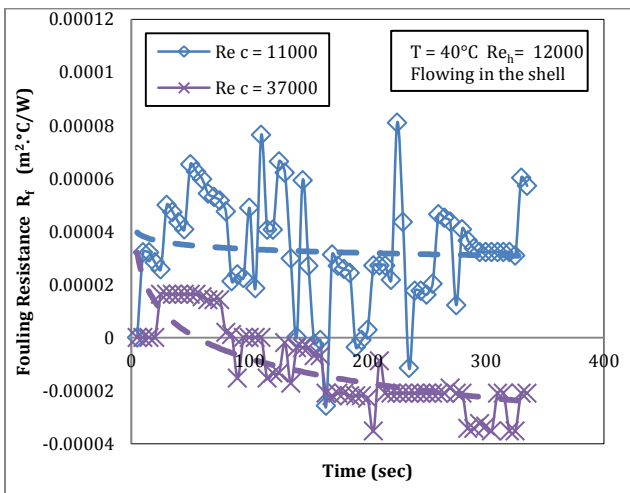


Fig.16 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 12000$ for different Re_c values

Sawtooth phenomena are also present in Fig.16 while fouling behavior changes to the linear for $Re_c = 11000$ and falling rate for $Re_c = 37000$ as the velocity of the hot salt solution increases to $Re_h = 12000$. The linear curve trend is also is characteristic of fragile deposits which remove easily as a result of the shear force of the flow (Helalizadeh et al., 2000).

Negative values of thermal resistance can be seen in Fig.14, Fig.15, and Fig.16. As crystalline layer buildup it leads to an increase in the surface roughness and subsequently the local heat transfer coefficient increases, therefore, the calculated thermal resistance portraying a negative value (Mwaba et al., 2006a).

Effect of glass beads addition to the foulent solution of Na_2SO_4 in shell side on the removal of the crystalline layer is represented by its effect of thermal resistance values in Fig.17, Fig.18, and Fig.19 at glass beads concentration of 1.25 g/l; Fig.20, Fig.21, and Fig.22 at glass beads concentration of 0.625 g/l. with a constant temperature of $T = 40^\circ\text{C}$ and full investigated ranges of Re_h and Re_c values of 11000 and 37000.

For a salt solution with glass beads concentration of 1.25 g/l, in Fig.17, fouling rates for the two Re_c velocities selected shows a falling rates trends compare to the fouling rates under the same operating conditions but with glass beads-free salt solution. The trends in Fig.14 are asymptotic for $Re_c = 11000$ and linear trend for $Re_c = 37000$. This change in fouling rate trend is due to the cleaning action of glass beads that prevent the buildup of fouling with time. An increase in the values of fouling resistance is evident this attributed to the decrease in the values of the local heat transfer coefficients due to the change in hydrodynamics condition in the test section rather than fouling effect (Jamialahmadi et al., 1992).

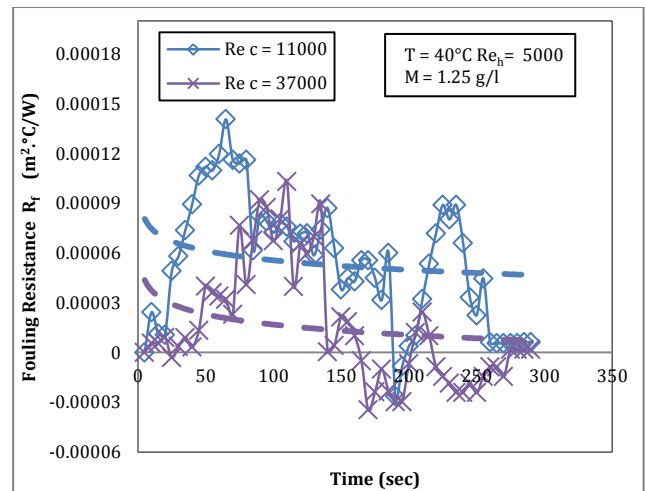


Fig.17 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 5000$ for different Re_c values, (Presence of glass beads $M = 1.25$ g/l)

In Fig.18 and Fig.19 the fouling resistance values at $Re_c = 11000$ is greatly reduced compared to fouling resistance values of glass beads – free salt solution in

Fig.15 and Fig.16 and showing a falling rate trend. For $Re_c = 37000$ in Fig.18 and Fig.19 an asymptotic fouling rate with some increase in fouling resistance values as explained before this is due to the change in hydrodynamics.

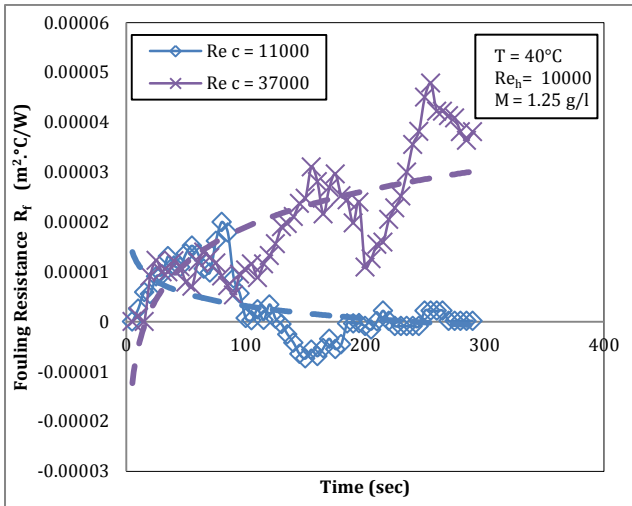


Fig.18 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 10000$ for different Re_c values, (Presence of glass beads $M = 1.25$ g/l)

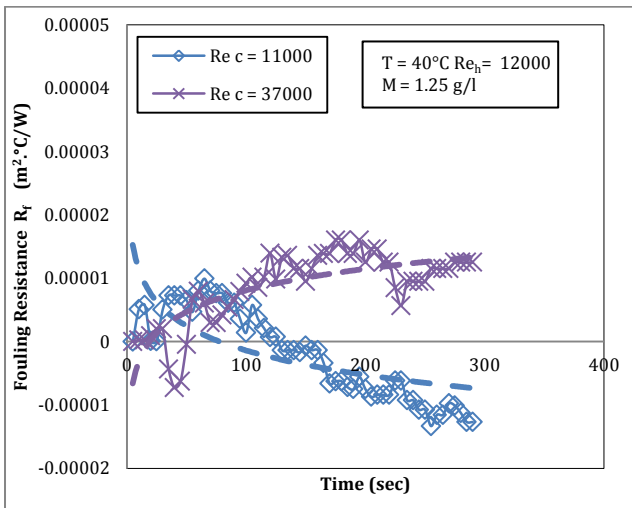


Fig.19 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 12000$ for different Re_c values, (Presence of glass beads $M = 1.25$ g/l)

For salt solution with glass beads concentration of 0.625 g/l, in Fig.20 asymptotic fouling rate for both values of Re_c is noticed, values of fouling resistance at $Re_c = 11000$ is reduced as compared to glass bead - free case in Fig.14 and the glass bead concentration 1.25 g/l case in Fig.17 under the same operation conditions, while fouling resistance values at $Re_c = 3700$ shows an increase in its values.

As the velocity of hot salt solution containing glass beads increases to $Re_h = 10000$ in Fig.21 fouling

resistance for both Re_c values shows a further reduction in its values with $Re_c = 11000$ portraying falling trend and $Re_c = 37000$ having an asymptotic trend.

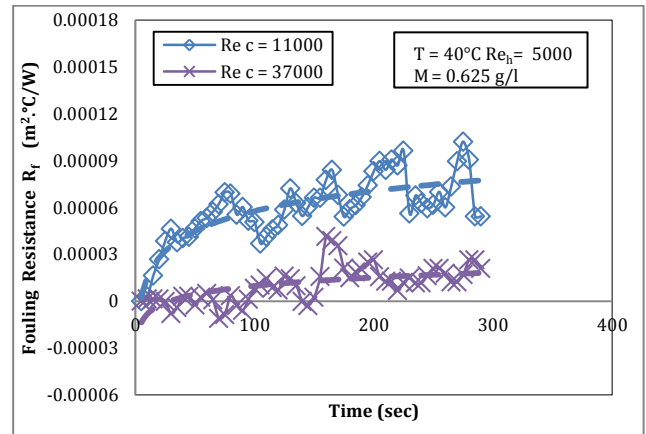


Fig.20 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 5000$ for different Re_c , (Presence of glass beads $M = 0.625$ g/l)

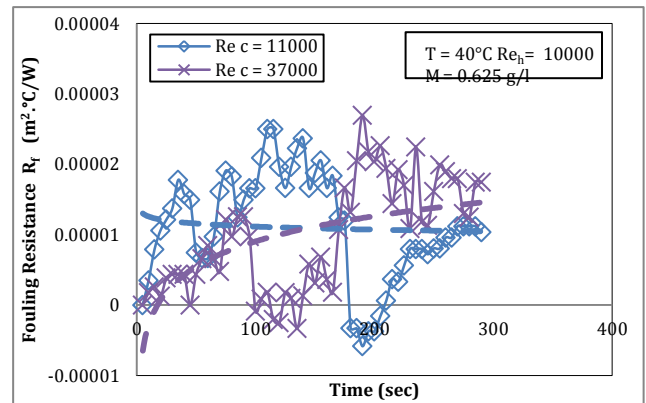


Fig.21 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 10000$ for different Re_c values, (Presence of glass beads $M = 0.625$ g/l)

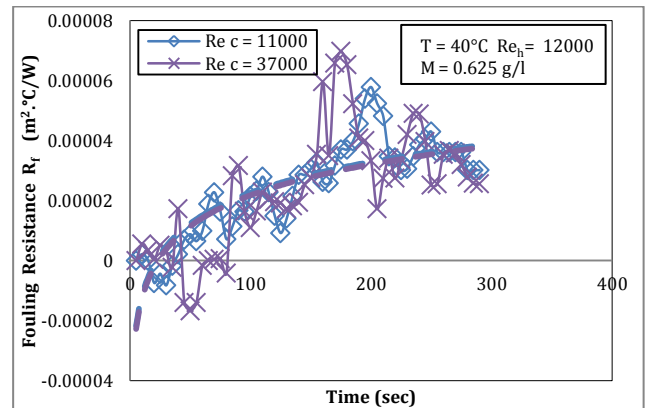


Fig.22 Variation of Fouling Resistance with time at constant temperature $T = 40^\circ\text{C}$ and $Re_h = 12000$ for different Re_c values, (Presence of glass beads $M = 0.625$ g/l)

In Fig.22 fouling rates shows again an asymptotic trend with improvement in fouling resistance value compare to the cases in Fig.16 for salt solution free of glass beads and Fig.19 at glass beads concentration of 1.25 g/l, which is also as a result of hydrodynamic changes.

Conclusions

The main findings from the present work are listed below:

- 1) Crystallization fouling results in a reduction in the values of heat transfer coefficients by (20%~45%); this reduction has an inverse proportionality with the Reynolds number of the hot solution.
- 2) There was an increase in the values of the overall heat transfer coefficients with the addition of circulating glass beads within the foulent solution; this increase was significantly higher with smaller concentration (12%~740%) for (0.625 g/l) and (16%~400%) for (1.25g g/l).
- 3) Decreasing the flow velocity of the glass beads increases the values of heat transfer coefficients.
- 4) Different fouling rates behaviors were present depending on the operation condition.
- 5) Change in the mechanism of fouling from mass control to surface temperature control as the Reynolds number of the hot solution in the shell side increases.
- 6) Prevention of crystalline layer built up was possible due the circulation of glass beads in the foulant solution

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