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Research Article

Mitigation of Crystallization Fouling in Double Pipe Heat Exchanger using Glass Beads

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Abstract

Crystallization fouling experiments where preformed for double pipe heat exchanger under counter flow condition in which sodium sulfate (Na_2SO_4) at saturation condition and constant bulk temperature of (32°C) where made to flow in the shell at different Reynolds number (Re_h = 5000-12000), cold water flowing the pipe at constant temperature of (12°C) at different Reynolds numbers (Re_c = 11000-37000).The overall heat transfer coefficient were determined from the measurement of the inlet and outlet temperature of the system at the given different velocities. Glass beads (3mmØ) at two different concentrations (0.625-1.25g/l) where introduced to the process fluid (salt solution) to mitigate fouling. The experimental results showed that the enhancing effect of glass beads on heat transfer is more pronounced at lower velocities and lower concentration.

Keywords: *Crystallization fouling, Heat Exchanger, Heat transfer coefficient, Glass bead, Mitigation*

1. Introduction

Heat exchangers are devises that allow the exchange of heat between two fluids that are at different temperatures without mixing with each other. They are commonly used in wide range of application from house holding to chemical processing and large power plants (Yunus and Robert, 2005). After a period of operation the heat transfer surfaces for a heat exchanger may become coated with various deposits that may be present in the flow systems, or it may become corroded as a result of the interaction between the fluids and the material used for construction of the heat exchanger. In either case, this coating represents an additional resistance to the heat transfer, and causes a decreased performance (Holman, 2010). 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 common type of fouling in the aqueous systems, for example system using water for cooling purposes or evaporative desalination (Bott, 1995).

Many studies in the literature investigated crystallization fouling and factor effecting it, in their experimental work (Khan *et al.*, 1996) studied the influence of tube surface temperature, Reynolds number, and tube diameter on precipitation of $CaCO_3$ in double-pipe counter flow heat exchanger. The experimental results showed that influence of Reynolds number is almost negligible in the range investigated (Re = 900-1700). With regard to tube surface temperature and tube diameter influence on the fouling growth was found to be considerable for the range investigated.

In their study, (Yang *et al.*, 2002) investigated the $CaCO_3$ fouling in both cooling water and pool-boiling systems, the induction period as well as the removal of fouling was studied. The self-assembled monolayers low-energy surface can delay the induction period of fouling in the cooling water system compared with the copper surface. With decreasing initial surface temperature and fluid velocity the induction period increases.

When the heat flux is fixed in different experiments, an increase in the fluid velocity will result in a decrease in the initial surface temperature. Under this condition, the induction period increases with increasing fluid velocity as a result of the interactional effects between surface temperature and fluid velocity. The removal experiments were carried out both in the induction period and in the post-induction period. The results show that only in the induction period can the fouling resistance be reduced as a result of the weaker adhesion strength of fouling. Introducing antifoulant polyacrylic acid (PAA) to the bulk result in the change of crystal forms and the fractal dimensions of $CaCO_3$ morphologies increase for both the cooling water and the pool-boiling systems.

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

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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.

Investigation on the fouling behavior of saturated solution of $CaSO_4$ was conducted 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. Based on measurement of roughness effect due to fouling on pressure drop and on convective single phase heat transfer its found that both characteristic are almost symmetrical. Furthermore, 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.

Various methods were used in the previous studies to mitigate crystallization fouling. Method can be classified into basic categories: chemical methods, physical techniques and mechanical approach.

On-line chemical fouling mitigation, such as scale inhibitors, is effective but the chemical agents may contain substances that are potentially harmful to the environment (Müller-Steinhagen *et al*., 2011)

Physical water treatment (PWT) is a non-chemical method to mitigate mineral fouling with the use of electric or magnetic fields, catalytic surfaces, ultrasounds, or sudden pressure changes. (Tijing *et al*., 2010) investigated the feasibility of RF (radio frequency) electrical fields in mitigating $CaCO_3$ fouling in cooling water. RF electric fields can generate between two graphite electrode plates directly in water. The fouling resistances for the PWT-treated cases dropped by 34–88% compared with those obtained for the no-treatment cases, depending on the cold-side flow velocity and the water hardness.

The mechanical cleaning action of various projectiles for fouling of calcium sulfate was performed inside a heated tube was investigated by (Jalalirad *et al*., 2013). Results show the flexible sponge balls are more efficient than rigid rubber balls. Larger and harder sponge balls are more effective than smaller and softer types only if they can be propelled inside the tube. Rigid balls with exact diameter of the pipe inner diameter would even worsen the deposition process as they may compact the deposit on the inner wall causing even a harder and more compact deposit.

An interesting continues clean method has been investigated over the past years where solid particles of different materials being circulated through the heat exchanger.

In their study, (Kim *et al*., 1996) investigated the effect of glass beads (3mmØ) 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 than1.0 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 mmØ, 3 mmØ, 4 mmØ) 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 concluded that the increase in heat transfer coefficient was in order of sand, copper, steel, aluminum, and glass this behavior might be associated to 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 mmØ compare to 2 mmØ diameter particles at lower velocity, this is could be related to the fact that the particles of 2.5 and 3 mmØ 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.

In the present work, an experimental study has been conducted to investigate the cleaning action of glass beads at different concentration on crystallization fouling of Na_2SO_4 salt in double pipe heat exchanger under different flow conditions.

2. Material and Method

The experimental apparatus as shown in detail in Fig. 1 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} = 15mm, 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 600×600×400 mm to service as hot fluid resource equipped with heater. The tank was filled with tap water where it was heated to the desired temperature before being pumped into the test section. Salt solution replaces the tab water in the tank later and also pumped into the test section. Chiller with 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°C before being pumped to the heat exchanger.

Two centrifugal pumps was 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 (32°C). Other 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°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.

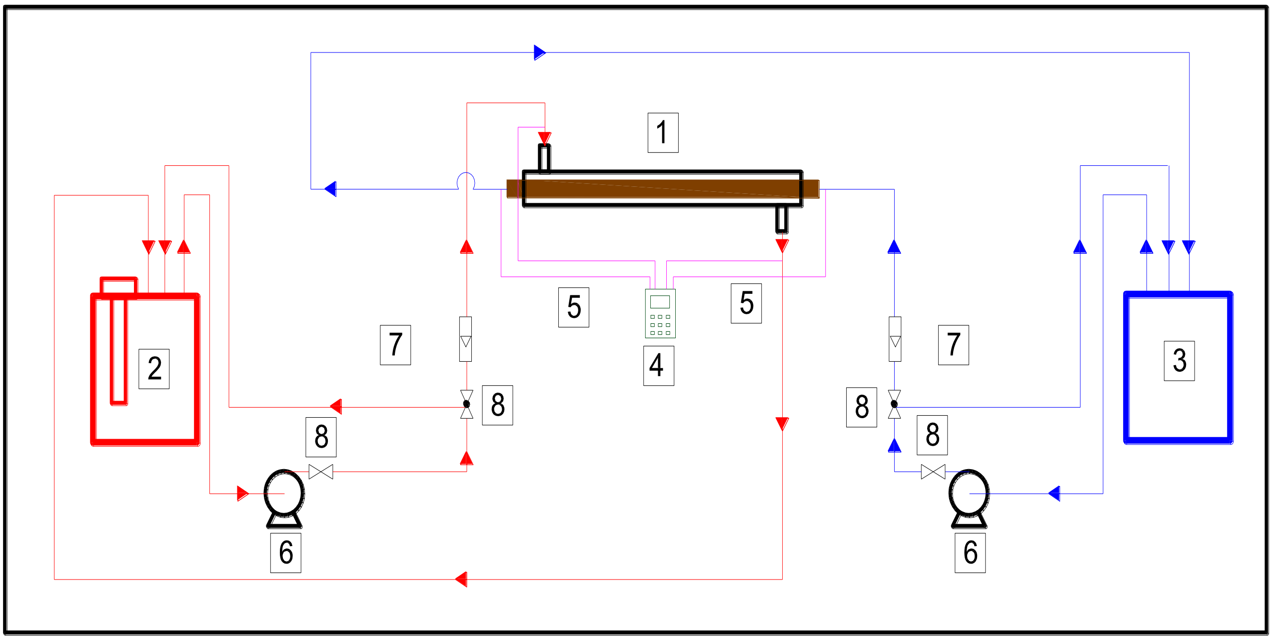


Fig.1 Schematic diagram of experimental apparatus

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

The thermocouples were calibrated using cold water of known temperature and found to have ± 0.1°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°C with the cold fluid temperature was maintained at 12°C.

The second sets of experimenters were to study the effect of crystallization fouling on the performance of heat exchanger. The hot fluid tanks 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).

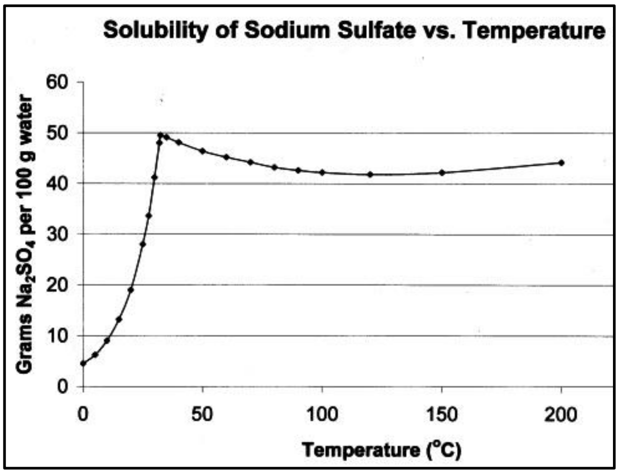


Fig.3 Solubility of sodium sulfate as a function of temperature (Linke and Seidell, 1965).

At the start of each experiment, the heater and chiller were set on the required temperature. Then the control valve was opened and pump started to flow the hot water through the rotameter and, the outer tube of the double pipe heat exchanger. Waiting one minute to circulate the hot flow and reach a constant surface temperature. 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 growth of crystalline layer.

Temperatures of four points two at inlet and two at outlet of each fluid were recorded from start of heat transfer process between the two fluids. The temperature reader was set to record the data every five seconds.

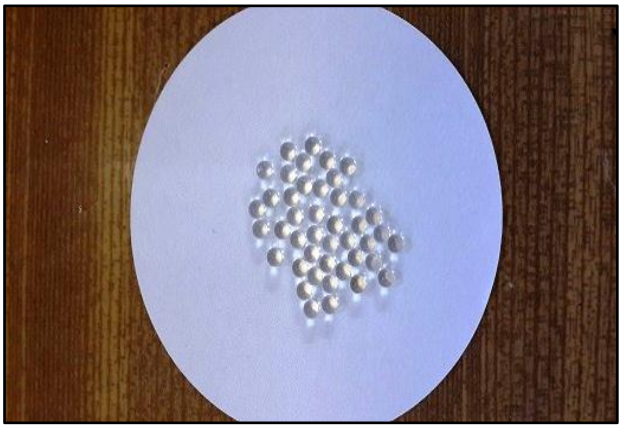


Fig.4 Photographed picture of glass beads

An on-line physical mitigation technique was used to combat the crystallization fouling effect. Glass beads (3mmØ) as shown in Fig.4 where 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 ±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).

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:

$$q_h = \dot{m}_h C_{ph}\left(T_{hi} - T_{ho}\right) \quad (1)$$

$$q_c = \dot{m}_c C_{pc}\left(T_{co} - T_{ci}\right) \quad (2)$$

Where q_h, q_c, $\dot{m}_h$, $\dot{m}_c$, C_{ph} and C_{pc} are the heat transfer rate to 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:

$$U_o = \frac{q}{A_o \Delta T_{LMDT}} \quad (3)$$

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 long mean temperature difference will be:

$$\Delta T_{LMDT} = \frac{\left(T_{hi} - T_{co}\right) - \left(T_{ho} - T_{ci}\right)}{\ln \frac{\left(T_{hi} - T_{co}\right)}{\left(T_{ho} - T_{ci}\right)}} \quad (4)$$

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

$$\mathrm{Re} = \frac{\rho u D}{\mu} \quad (5)$$

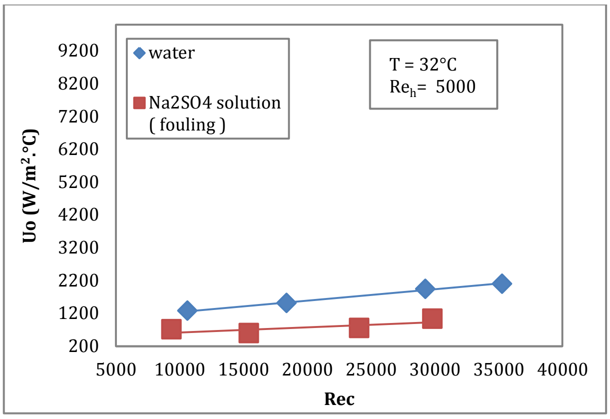
The diameter for the case of fluid flowing in the inside tube flow will be D_{it} = 15 mm, as for annulus flow case the hydraulic diameter will be used:

$$D_H = D_{is} - D_{ot} \quad (6)$$

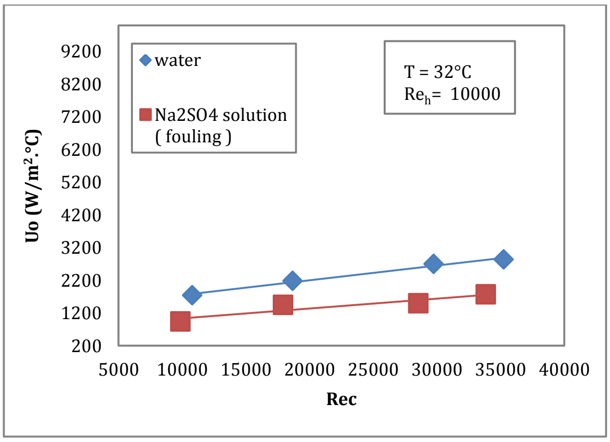
which well equal to D_H = 28 – 16 = 12 mm.

3. Results and Discussions

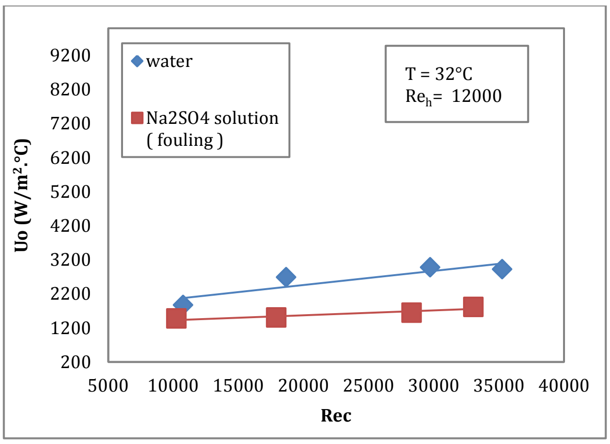
A series of experiments was conducted to investigate the effect of crystallization fouling on the overall heat transfer coefficient Fig.5 shows the effect of the formation of crystal layer of Na_2SO_4 salt on the outer surface of the inside tube of the heat exchanger.



(a) Re_h = 5000



(b) Re_h = 10000



(c) Re_h = 12000

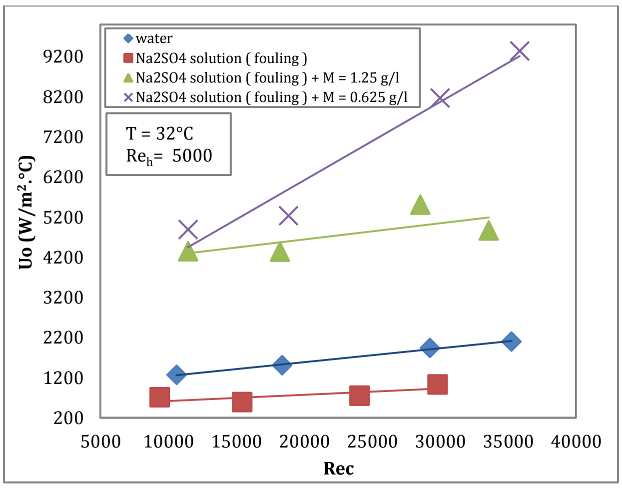
Fig.5. a, b, c. Effect of fouling (Na_2SO_4) on the overall heat transfer coefficient for a whole investigated range of Reynolds Number

As the supersaturated hot salt solution flows in the annuals, the cold water flowing in the inside tube decreasing the surface temperature of the pipe outer wall leading to the formation of crystalline layer (since Na_2SO_4 is a normal solubility salt that form a crystal as its solution temperature decreases) on the outer surface. The crystallization of the salt on the surfaces increases the thermal resistance to heat transfer due to its low thermal conductivity resulting in a decrease in the overall heat transfer coefficient by magnitude of 30% ~ 50 % for the whole range of salt solution Reynolds numbers. Similar behavior was noticed by (Hasan *et al.*, 2012) in their study of crystallization fouling of saturated sodium sulfate (Na_2SO_4) over a pipe containing cold water under cross flow condition.

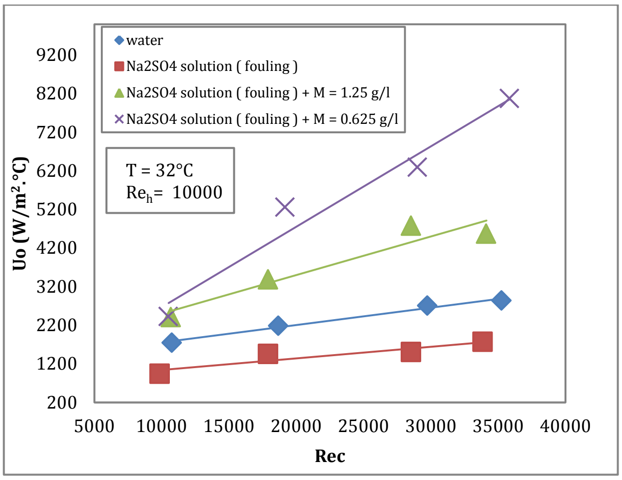
The percent reduction in the overall heat transfer coefficient of salt solution from that of water decreases with the increase of Reynolds numbers of the hot solution. Similar effect of increasing flow velocity was observed by (Hasson and Zahavi, 1970) investigate $CaSO_4$ scale deposition in an annular heat exchanger shows that scale-layer growth decrease with increasing 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.

This indicates that fouling process in the present work is under surface attachment mechanism. Another explanation of these phenomena was introduced by (Hasan *et al.*, 2012), as the velocity of the solution increases the temperature of the heat transfer surface increase which result in dissolving of crystal layer (Na_2SO_4 is a normal solubility salt) hindering its effect on overall heat transfer coefficient.

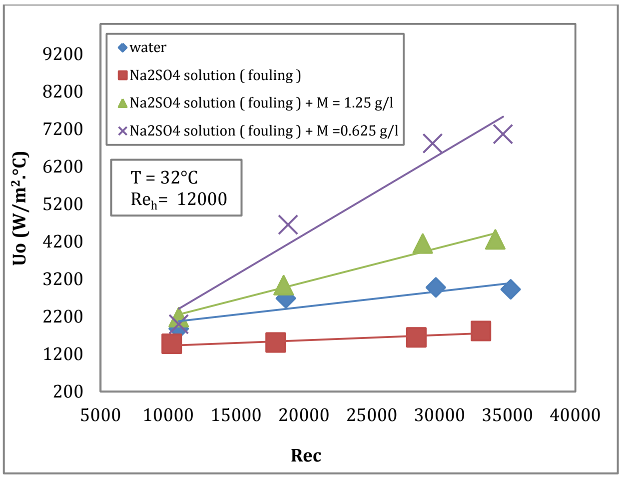
To minimize the effect of crystallization fouling on the heat transfer process, glass beads (3mmØ) where introduced to the salt solution at two different concentrations. Fig.6 shows the effect of glass beads addition at two studied concentration on the values of the overall heat transfer coefficients, an increase in the overall heat transfer coefficient was noticed.



(a) Re_h = 5000



(b) Re_h = 10000



(c) Re_h = 12000

Fig.6.a, b, c. Effect glass beads at different concentration on the overall heat transfer coefficient for a whole investigated range of Reynolds Number

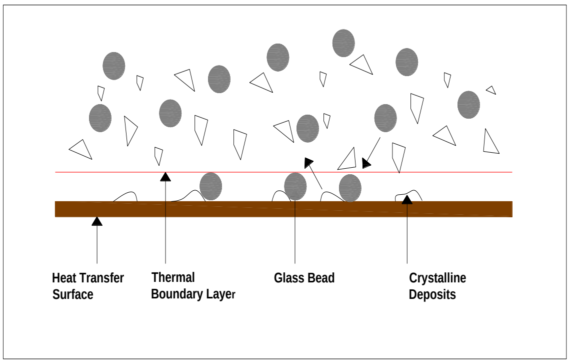
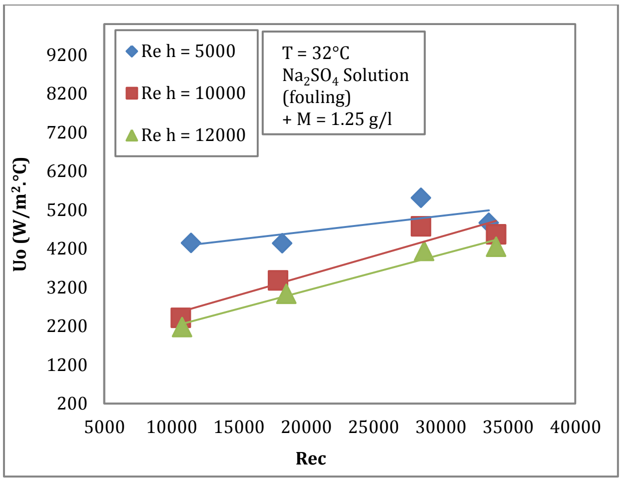


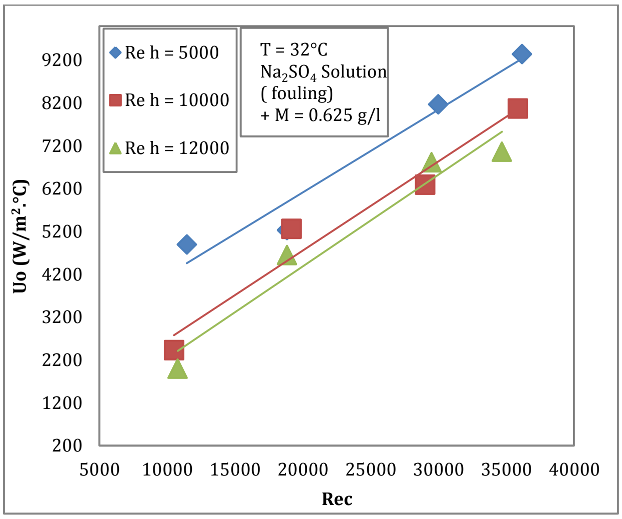
Fig.7 Schematic diagram illustrates the cleaning action of glass beads and the breaking of thermal boundary layer (Kang *et al.*, 2011)

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 continues removal of foulant layer by the solid particles as they continuously hit the heat transfer wall, as illustrated in Fig.7, 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 sub layer 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.6 the lower concentration (0.625 g/l) of the glass beads in the foulant solution gives a greater enhancement compare to the higher concentration (1.25 g/l) its 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 rabid leading to more cleaning action and disturbing to the laminar sub layer giving a better heat transfer rate.



(a) Glass beads concentration M = 1.25 g/l



(b) Glass beads concentration M = 0.625 g/l.

Fig.8. a, b. Heat transfer coefficient of glass beads – foulent solution at different hot solution Reynolds Numbers

The experimental results in Fig.8 show 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 to an increase in the hitting frequency and thus increase the overall heat transfer coefficient.

Conclusion

An experimental investigation on the effect of crystallization fouling of Na_2SO_4 salt on the overall heat transfer coefficient, Furthermore, the cleaning action on fouling through the circulation of glass beads in the heat exchanger was tested. The main findings are listed below:

1) Crystallization fouling reduces the heat transfer rates by percentage of 30%~50%; 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 (200%~800%) for (0.625 g/l) and (100%~550%) for (1.25g g/l).
3) Decreasing the flow velocity of the glass beads increase the values of heat transfer coefficients.

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