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Experimental Study of Scale Formation in Sea Water Environment

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Abstract. Seawater is a complex aqueous solution with large tendency for scale formation, which is usually ascribed to the scaling dissolved salts and suspended particles. Scale formation results in lots of problems in thermal processes like desalination and steam generation plants. In a typical desalination plant, about 40% of the heat transfer is provided to allow for scale formation problems, which is equivalent to about 10% increase of the whole capital cost of the plant. The main constituent forming scale in seawater environments (calcium carbonate, calcium sulfate and magnesium hydroxide) is extensively investigated in the present work. For better understanding of the scale tendency of seawater environment, an experimental unit was precisely designed and coupled with data acquisition system for continuous monitoring of the investigated parameters. Significant factors affecting scale formation like salts concentration, flow velocity, water temperature and pH of the environment were extensively studied using mild steel and stainless steel (rough and smooth). The hydraulic parameters like Reynolds number and shear stress were used in the analysis of the collected data and revealed the role of shear stress in the effective removal of scale. The scale model of Kern and Seaton was used to calculate the fouling resistance in each case and values obtained were compared with the experimental ones. A modification of this model was also attempted to give better agreement with the experimental findings.

Introduction

Scale formation is still a major operating problem encountered in seawater environments. Most people working in seawater desalination plants recognize that scale formation and fouling problems are facts of their practical life. Among the main problems encountered with scale formation in desalination plants, one can mention; the significant reduction in the thermal performance of the plant, the loss of water production, increase of pressure requirements, and increase in both maintenance cost and capital cost. Hence, the avoidance, detection and removal of scale buildup constitute a substantial portion of capital and annual operation expenses in desalination plants.

Despite the increasing number of experimental and theoretical investigations on scale and fouling, it is still not possible to predict the actual fouling (or scale formation)

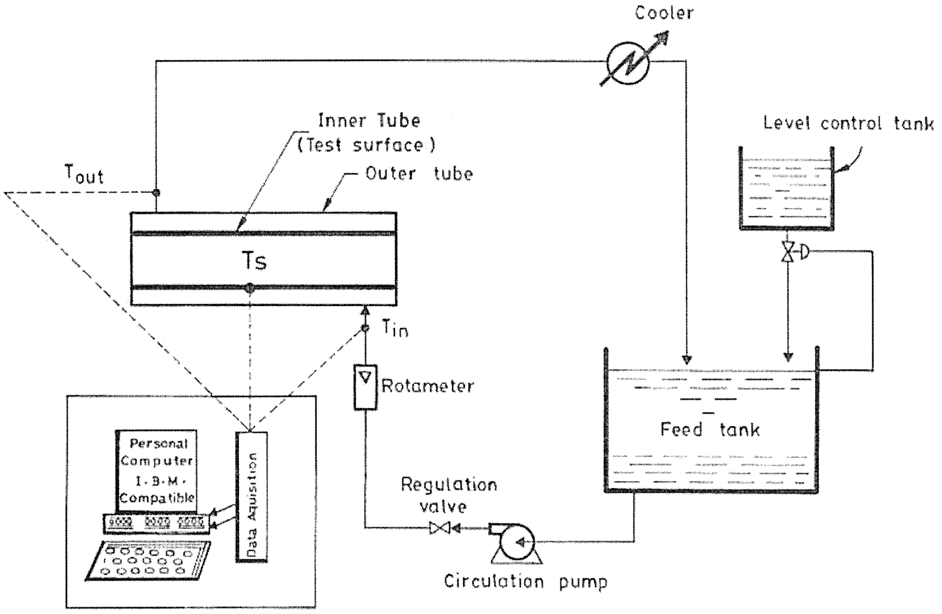

Fig. 1a. The circulating test loop.

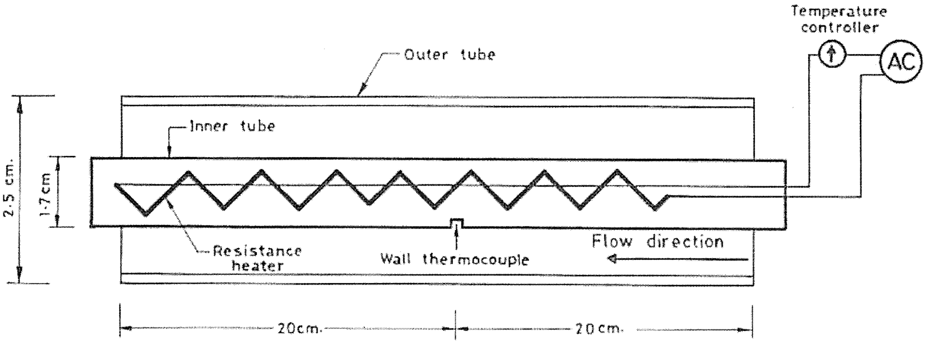

Fig. 1b. The test section with its cartridge heater.

rates in heat transfer systems under various operating conditions [1, 2].

From the practical point of view, the main constituents forming scale in seawater environments are calcium carbonate, calcium suphate and magnesium hydroxide.

A lot of research work appeared in literature concerning calcium carbonate scale [3-5] in contrast to calcium sulphate studies which are limited [6]. Hence, more attention is given in the present work for this type of scale due to its practical importance especially in desalination plants.

The main factors affecting scale formation like salt concentration, operating temperature, fluid velocity, pH of water environment, type of material and roughness are mainly considered in the present work. An experimental set-up is especially designed for this investigation in which mild steel and stainless still (smooth and rough) are used as heat transfer surfaces.

Kern-Seaton model was used for simulating the experimental fouling data after certain modification to account for stainless steel data.

Experimental Set-up

The experimental set-up used in the present work is shown in Fig. (1.a, 1.b). It consists of a closed circulation loop with its test section. The circulation loop contains a feed tank (for preparation and adjusting the test solutions) with its level controller and the circulating pump. The loop has also a cooler to adjust the temperature of the exit solution from the test section before entering into the feed tank. The loop is also fitted with its necessary measuring devices (as flow-meter and thermocouples). A data acquisition unit is also connected to the measuring points for accurate and continuous monitoring of the measured parameters via computer.

The test section, shown in Fig. 1.b is of annular type in which the heat source is located at its central core while the test fluid is flowing in the annular region. Thermocouples are used to measure the temperature of the heating surface as well as input and output bulk temperatures of the test solution. A cartridge electrical heater was used as a heating element to give a constant heat flux.

For each run the weight of the test section was obtained at the start and the end to find the mass of the fouling deposit from which the fouling resistance R_f was calculated and compared with the values obtained from heat transfer measurements.

The investigated parameters in the present work are; salt concentration, bulk temperature and surface temperature, velocity of the flowing fluid, time of deposit, pH of the scaling environment, type and roughness of the heat transfer surface. The volume of the feed tank in the experimental setup is 20 liters while the volume of the circulating loop is about 5 liters and the amount of scale deposited is very small compared to the amount of salts in the solution (less than 2 %).

Results and Discussion

a) The scaling potential of the various salts

In order to account for the scaling potential of the main considered salts ($CaCO_3$,

$CaSO_4$ and Mg $(OH)_2$) preliminary experiments were carried out at the same conditions (temperature at 40, pH at 8 and velocity at 0.25 m/s. In these experiments the duration time was 48 hours. Mild steel tubes were used in the test section.

The solutions were saturated at ambient temperature 25°C and over saturated at 40°C due to inverse solubility of these salts. Large scaling potential for $CaSO_4$ was noticed which give an evidence to start with $CaSO_4$ rather than other salts. At the end of each run, the weight of the deposit was obtained and the data collected are plotted in Fig. 2.

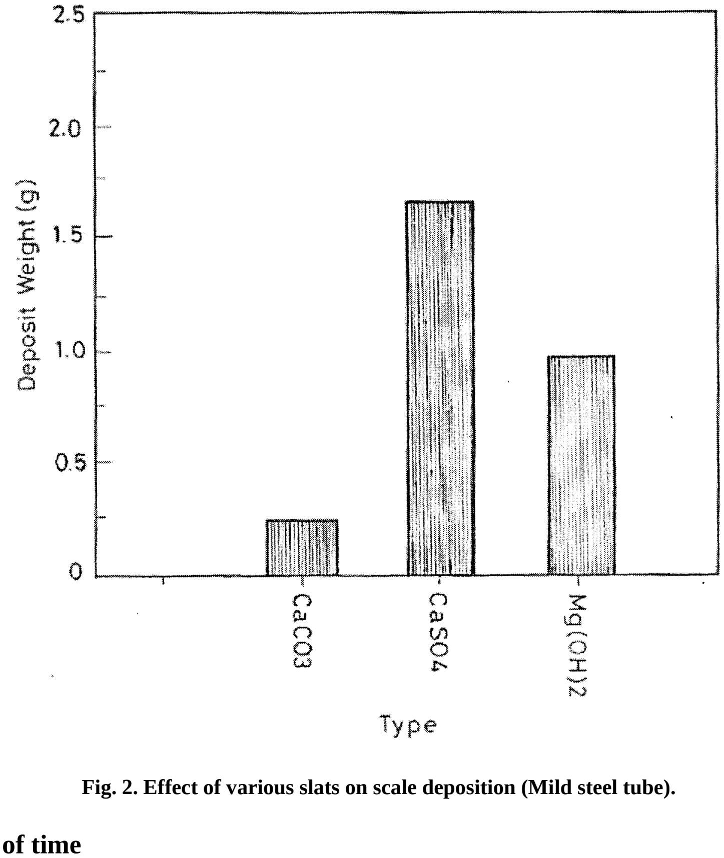

Fig. 2. Effect of various slats on scale deposition (Mild steel tube).

b) Effect of time

As fouling is a time dependent process, various experimental runs were carried out at various intervals (ranging from 24 hours to 720 hours) to reveal the effect of this parameter and also to achieve the steady state fouling conditions. Three types of materials were used in these runs, i.e. mild steel, stainless steel and roughened stainless steel.

For each material, various fouling experiments were carried out and the weight of the scale deposit was obtained after each interval and fouling time curve was plotted and a sample of these curves is given in Fig. 3 for the stainless steel tube.

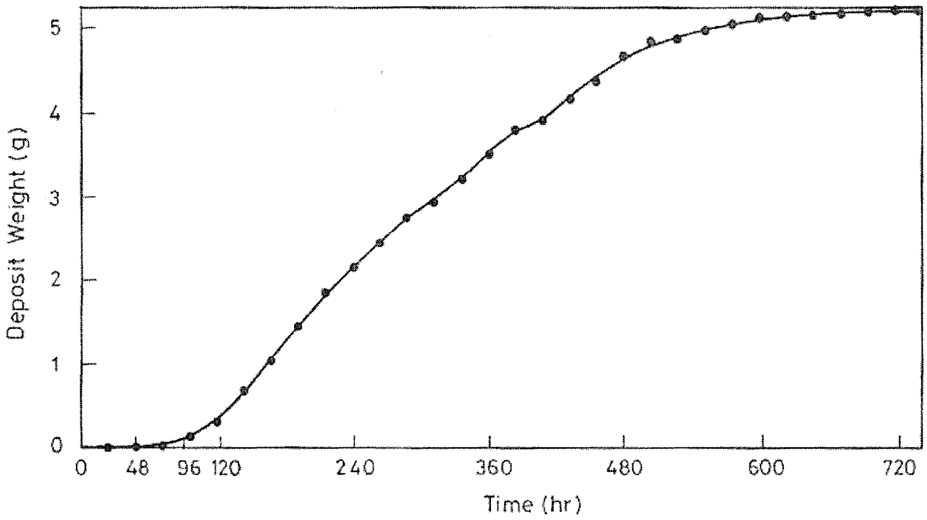

Fig. 3. The change of deposit weight with time (Styainless steel tube) (Condition: $CaSO_4$ conc. 1000 ppm, u = m/s, Re = 2000, Ti = 40 C, pH = 8, q = 31082.03 W/m^2.

As shown in this figure, a steady state value of the deposit was reached after about 624 hours. Calcium sulphate scales started to form after 72 hours of incubation period.

It is worth mentioning that; the asymptotic nature and incubation period of Fig. 3 are very similar to other fouling curves reported in the literature [7]. In case of mild steel and rough stainless steel no incubation periods were detected and their steady state deposits were achieved after relatively shorter times (for mild steel (408h) and for rough stainless steel (360h).

c) Effect of calcium suphate concentration

For mild steel (Fig. 4), $CaSO_4$ concentration was changed from 500 ppm to 1500 ppm while the other parameters were kept constant. It is clear that fouling deposit increases directly by increasing the concentration of $CaSO_4$ in the investigated fluid. This direct effect of salt concentration on fouling is expected as the thermodynamic driving force for scale formation is the supersaturation of the considered salt and hence increasing its concentration in water will increase the supersaturation and produce more scale deposit [8].

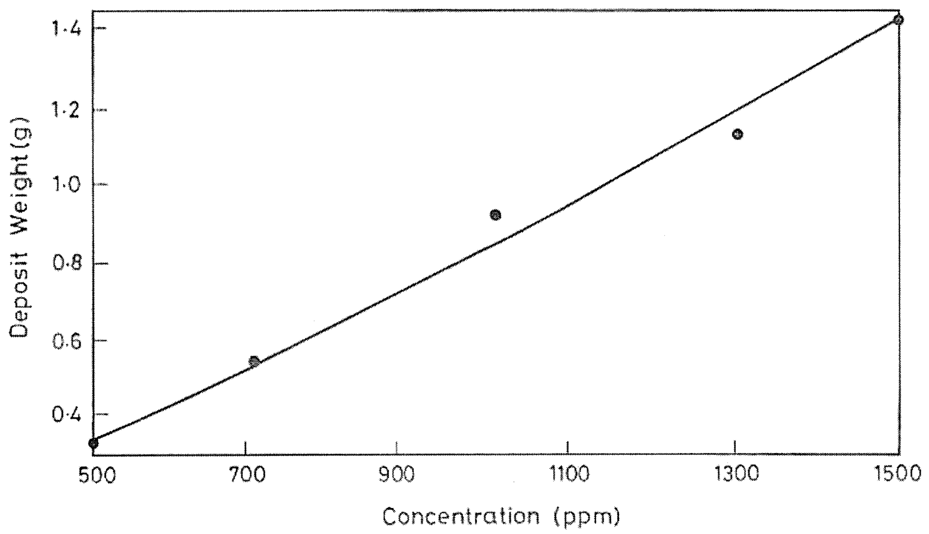

Fig. 4. Effect of $CaSO_4$ concentration on scale deposition (mild steel tube). Condition: u= 0.25 m/s, Re = 2000, Ti = 40 C, pH = 8, q = 31082.03 W/m^2, Time = 24 hr.

It is worth mentioning that, an interesting effect was observed during these concentration runs. It was found that the induction period of stainless steel decreased significantly (from 168 hr to 82 hr i.e about 50% reduction of its original value) by increasing the salt concentration from 500 to 1500 ppm. This significant reduction can be ascribed also to the supersaturation of calcium sulphate leading to the early production of scale nuclei and initiating the scale process on the stainless steel surface.

d) Effect of fluid velocity

The fluid velocity is an important parameter in the scale formation processes. For example in diffusion controlled process, the mass transfer of scale forming ions towards the heating surface is a strong function of the flow velocity. On the other hand, the removal processes of the scale deposit from the heat surface depend also significantly on fluid velocity [9].

In this work the flow velocity is increased from .05 to 0.37 m/s (corresponding to Reynolds number 400 to 29,600) and keeping the other factors constant.

As shown in Fig. 5 increasing the flow velocity reduces the fouling deposit significantly which indicates that the removal mechanism is the more controlling one in the present scale formation process. As shear stress is the most important factor in the removal process of scale deposit; precise calculations were carried out to compute the sheer stress at each investigated velocity and another plot was constructed between sheer stress and the weight of scale deposit as shown in Fig. 6. This figure indicates clearly that shear stress is the actual factor affecting scale reduction during the change of flow velocity [7, 10].

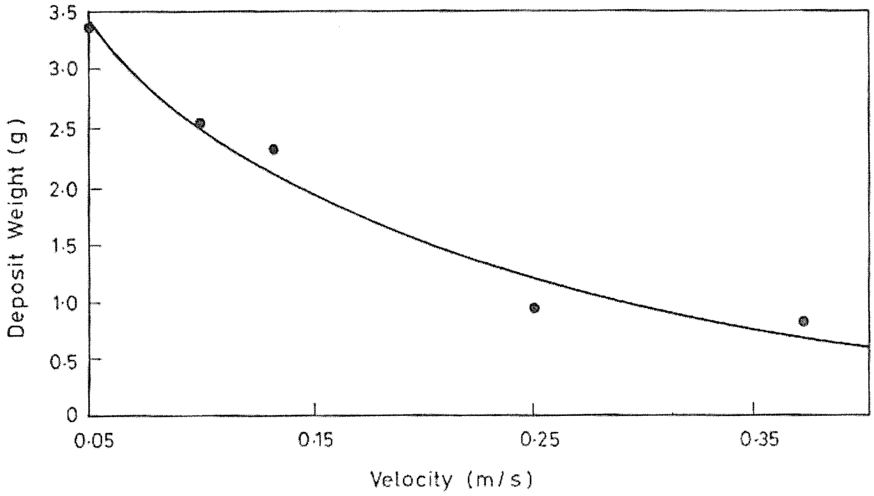

Fig. 5. Effect of flow velocity on scale deposition (mild steel tube). Condition: $CaSO_4$ conc. 1000 ppm, Ti = 40 C, Time = 24 hr, q = 31082.03 W/m^2.

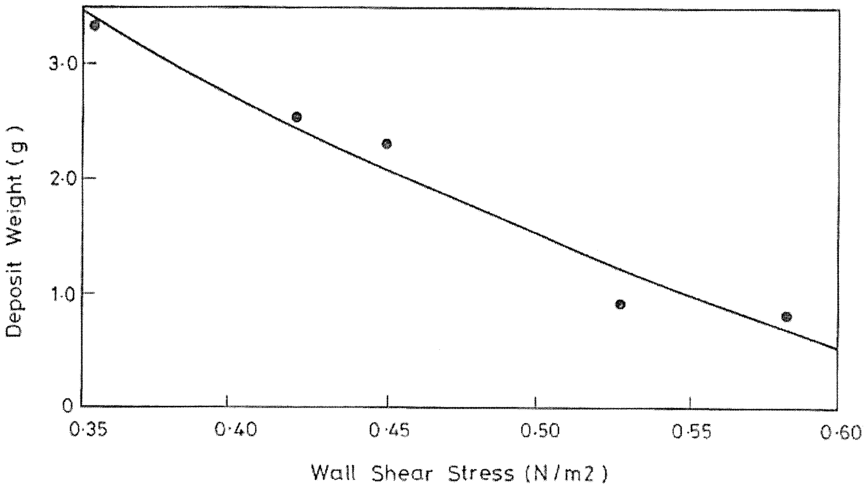

Fig. 6. Wall shear stress versus deposition weight (mild steel). Condition: $CaSO_4$ conc. 1000 ppm, pH = 8, Ti = 40 C, Time = 24 hr, q = 31082.03 W/m^2.

From the practical point of view, high velocities are recommended for use in desalination plants to reduce scale formation problems.

e) Effect of temperature

The fluid temperature plays an important rule in scale formation due to its effect on the supersaturation of the salts specially those who have inverse solubility behavior [9]. Hence, in the present work, the input temperature of the flowing fluid was varied and results obtained are plotted in Fig. 7 for the stainless steel tube.

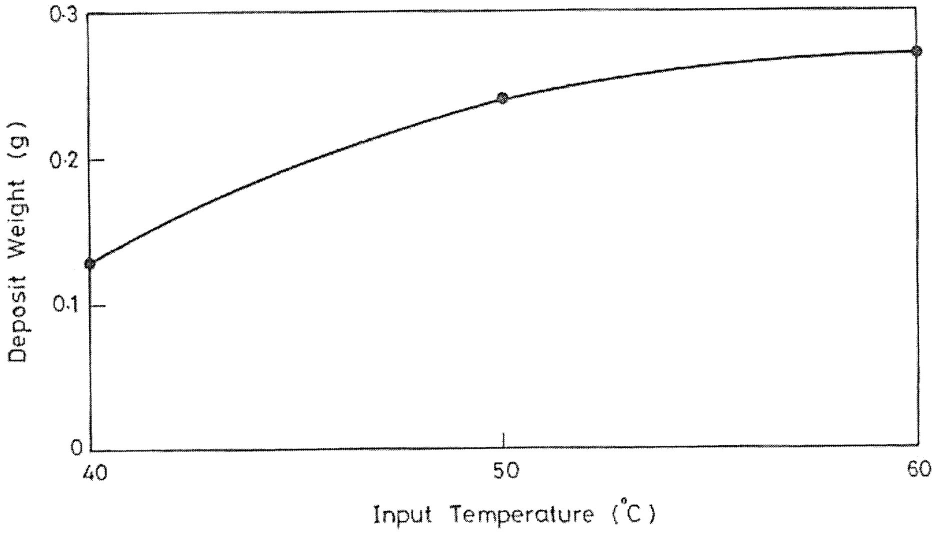

Fig. 7. The change of deposit weight with input temperature (stainless steel tube). Condition: $CaSO_4$ conc. 1000 ppm, u = 0.25 m/s, Re = 2000, pH =8, Time = 96 hr, q = 31082.03 W/m^2.

As shown in this figure, the scale deposit increases due to its effect on the super saturation of calcium sulfate. The effect of temperature on the incubation period of stainless steel was also extracted from these runs by precise observation of the time necessary for starting the deposition of the scale in each run according to this applied temperature and the data obtained are plotted in Fig. 8. The induction period decreases effectively by increasing the temperature of the flow due also to the increase in supersaturation, which produces early the nuclei of $CaSO_4$ necessary for starting the scale process.

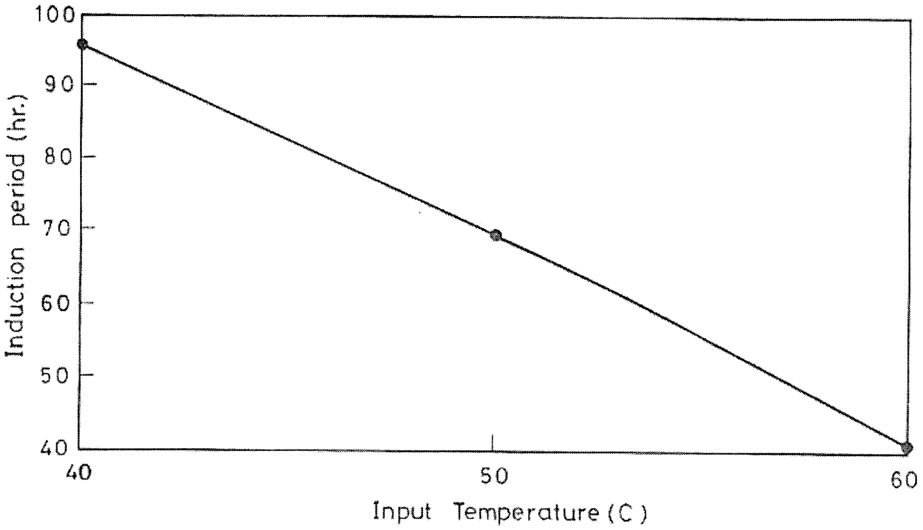

Fig. 8. Induction period vesus input temperature. (Stainless steel tube). Condition: $CaSO_4$ conc. 1000 ppm, u = 0.25 m/s, Re = 2000. pH = 8, q = 31082.03 W/m^2.

f) Effect of pH

This parameter has significant importance in scale formation studies. In practice, pH values of the flowing fluids are reduced by acid dosing to minimize scale formation. But on the other hand, this will produce a lot of corrosion problems, hence this parameter (pH) has to be thoroughly investigated to distinguish between its effects on both scale and corrosion problems. For this purpose a systematic study was conducted in the present work to isolate its effect on scale from that on corrosion for better understanding of both effects.

The pH of this solution was varied from 4 to 9 and the total deposit was obtained at the end of each run. These deposits were plotted versus pH of the tested solution in Fig. 9. This figure shows the mixed effect of pH on both scale and corrosion as it was noticed also from the quality of the deposit (yellow corrosion products were observed in it). Hence, precise chemical analysis were conducted on the collected samples of the deposit to isolate the corrosion products form $CaSO_4$ scales and the results were repotted in Fig. 10 versus pH of the test solution.

As shown in this figure scale is always present at higher pH values (>7) where corrosion increases sharply with decrease of pH. These findings are in good agreement with those reported in literature concerning the precise control of pH (at 6-7) to avoid both scale and corrosion problems in water systems [7]. It is worth mentioning that, in

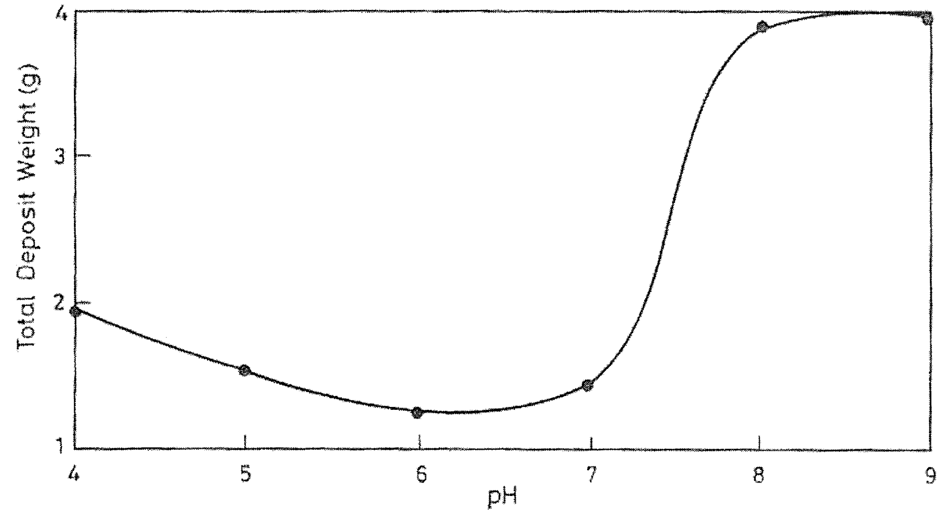

Fig. 9. The effect of pH on total depositin of calcium sulfate (mild steel). Condition: $CaSO_4$ conc. 1000 ppm, u = 0.25 m/s, Re = 2000, Ti = 40 C, Time = 144 hr, q = 31082.03 W/m^2.

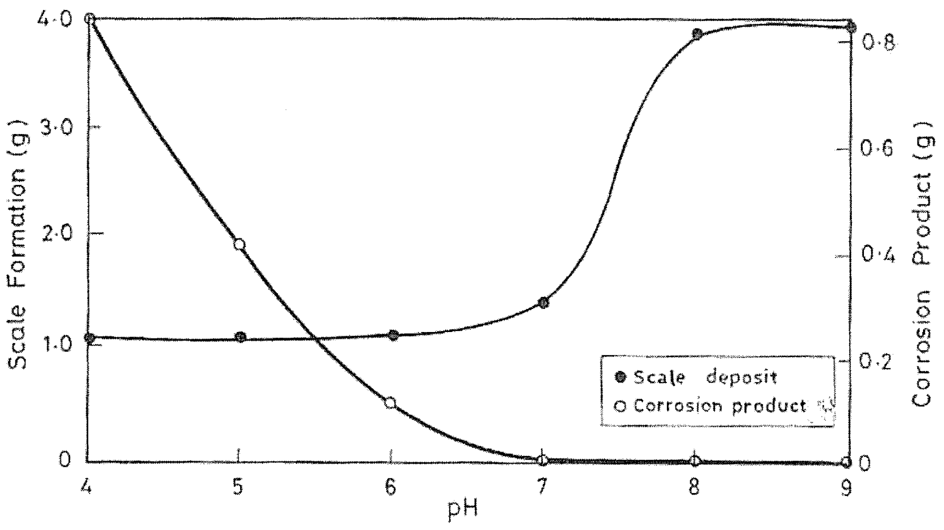

Fig. 10. The effect of pH on scale and corrosion (separately) (mild steel). Condition: $CaSO_4$ conc. 1000 ppm, u = 0.25 m/s, Re = 2000, Ti = 40 C, Time = 144 hr, q = 31082.03 W/m^2.

practice, acid dosing is applied in desalination plants to reduce scale formation. But this will generate a lot of corrosion problems, hence either corrosion inhibitor is to be added or precise control of pH around (6-7) has to be applied.

Modeling of the Collected Scale and Fouling Data

In an attempt to model the present experimental data, the fouling resistance (R_f) was first calculated from the weight values of the deposit, then scale models (like Kern-Seaton) were tried to compare its predictions with our experimental data.

To convert mass of the scale deposit into the corresponding fouling resistance, the following equations are used:

$$W = \pi /4[D_s^2 - D_o^2]\, L\, \rho_s$$

$$R_f = \frac{\ln (D_s/D_o)}{2\, \pi\, k_s L}$$

Where:

W	= weight of the scale deposit
D_s	= diameter of the deposit
D_o	= external diameter of the clean metal tube (test section)
L	= length of the test section
ρ_s	= density of the deposit
k_s	= thermal conductivity of the deposit
R_f	= fouling resistance

Then, Kern-Seaton [11] model of the following form was attempted to fit the present fouling data:

$$R_f = R^* \{1- \exp (-t / t_c)\}$$

Where

R_f	= fouling resistance
R_f^*	= asymptotic value of the fouling resistance
t	= fouling time
t_c	= the time constant

In comparing the model predictions with our experimental data, it was found that; the model succeeded only to fit the mild steel data (where no induction period exists), as shown in Fig. 11. But when we tried to use the same model for stainless steel, it failed to fit the data as shown in Fig. 12 hence we modified this model as follows:

$$\mathbf{R_f = R^* \{1\text{-}exp.} \left\{ \frac{-(t-t_D)}{t_c} \right\}$$

Where t_D is the time of the induction period.

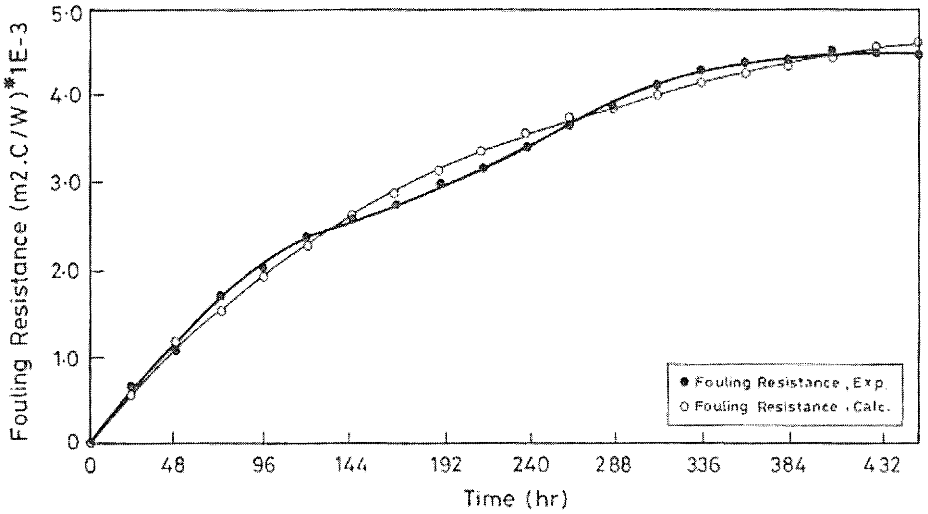

Fig. 11. Experimental and calculated fouling resistance from Kern & Seaton model for mild steel tube.

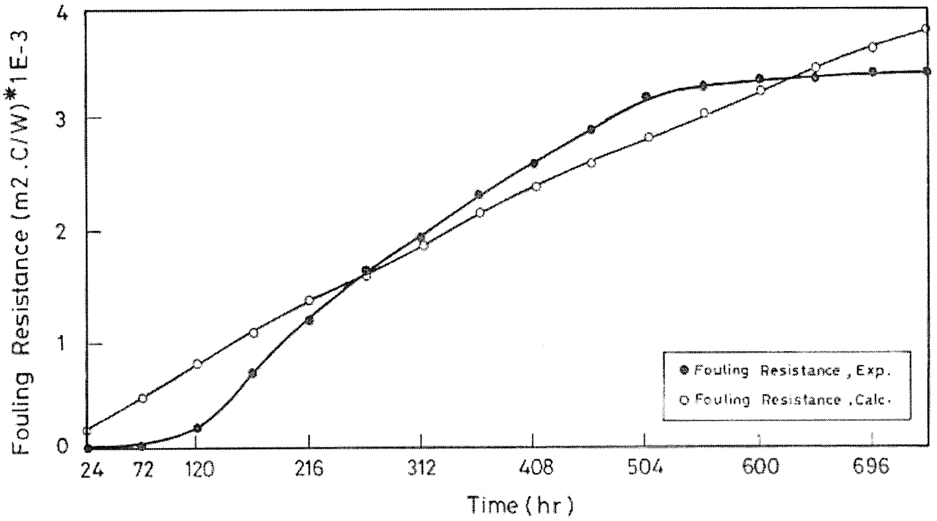

Fig. 12. Experimental and calculated fouling resistance from Kern & Seaton model for stainless steel tube.

Then, using this modified form to fit our data, better agreement was achieved as shown in Fig. 13. It is to be mentioned that; the initial negative results obtained in Fig. (13) indicate that no actual fouling exists in this induction period. Other investigators used this modified model to describe their fouling data [12].

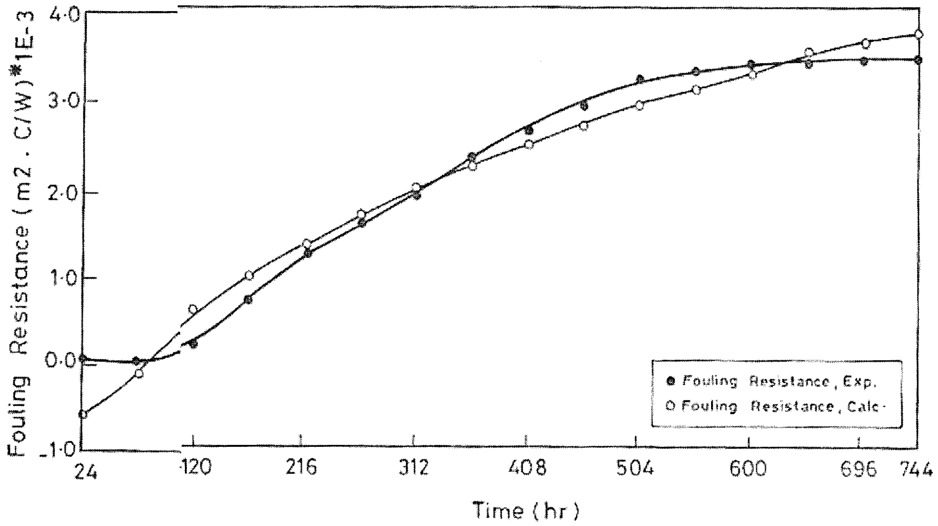

Fig. 13. Experimental and calculated fouling resistance from the modified Kern & Seaton model for stainless steel tube.

Conclusions

The present investigation led to the following conclusions:

1. The time dependence of scale formation in water environment has an assymptotic nature. The duration period for the steady state value of the scale deposit depends on the material of the heat transfer surface (stainless steel has larger period than both mild steel and rough surfaces).

2. An induction period of about 96 hours was detected only for stainless steel beyond which scale starts to be formed.

3. Both concentration of calcium sulphate and temperature affect strongly scale formation in water environment due to their direct effect on the super-saturation of this fouling salt.

4. The velocity of flow can reduce effectively the scale deposit due to the strong effect of shear stress on the removal mechanism of the scale layer.

5. The pH of the medium plays a significant role in both scale formation and

corrosion. At low pH values (4-6) corrosion is controlling while at high pH values (7-9) scale is predominant. Hence during the application of acid doses in desalination plants for scale control, a great attention must be given to corrosion problems.

6. Rough surfaces have more fouling tendency than smooth ones. Hence corrosion products can also accelerate scale formation effectively.

7. A modified model was achieved based on Kern-Seaton model in order to predict successfully the experimental data obtained in the present work.

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دراسة معملية لتكون الترسبات في بيئة مياه البحر

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(استلم في ٠٤/٠٤/٢٠٠٣م، وقبل للنشر في ٠٨/٠٢/٢٠٠٤م)

ملخص البحث. يعتبر ماء البحر بيئة مائية معقدة ذات ميل كبير لتكوين الترسبات بسبب الأملاح الذائبة والجزيئات العالقة. إن الترسبات تتسبب في الكثير من المشكلات في العمليات الحرارية مثل التحلية وإنتاج البخار. تقريباً ٤٠% من الطاقة الحرارية في محطات التحلية تذهب هدراً بسبب الترسبات، مما يمثل زيادة ١٠% من التكاليف الرأسمالية للمحطات. المكونات الأساسية للترسب (كربونات الكالسيوم، كبريتات الكالسيوم، هيدروكسيد الماغنيسيوم) تمت دراستها باستفاضة في البحث الحالي.

تم عمل جهاز معملي لدراسة الترسبات باعتماد نظام قراءة بالكمبيوتر. العوامل المؤثرة مثل تركيز الأملاح، سرعة السائل، درجة الحرارة و pH تحت دراستها باستخدام قضيب معدني من الحديد الصلب وآخر المطاوع. العوامل الأخرى مثل رقم رينولد وإجهاد القص تم تحليلها اعتماداً على النتائج المعملية. نموذج kern & Seaton استخدم لدراسة معامل مقاومة الترسبات، وتمت مقارنته بالنتائج المعملية. بناءاً على ذلك تم تطوير النموذج ليتلاءم مع النتائج الحالية.