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# Mitigation of hard scale deposition using projectiles for low temperature cooling water services

A. Zebardast[a], M.R. Malayeri[a,b,*]

[a]*School of Chemical and Petroleum Eng., Shiraz University, Shiraz, Iran, email: zebardast.am@gmail.com (A. Zebardasi), Tel. 0098-713-6473680, Fax 0098-713-6473680, email: malayeri@shirazu.ac.ir (M.R. Malayeri)*
[b]*Institut für Verfahrenstechnik und Umwelttechnik (IVU), Technische Universität Dresden, 01062 Dresden, Germany,*
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## ABSTRACT

One of the viable options to mitigate the formation of hard scales in exchangers of water services is to use projectiles as they may exert ample shear to dislodge deposits. Projectiles come in different types in terms of size, material, structure and texture which, in turn, each would have a different impact on mitigation performance. In this study, the deposition of $CaSO_4$ has been studied as hard scale in the cooling water services and desalination units. To do so, the experimental results of deposition and removal rates which obtained by using P02 projectile which is spongy and soft, has been investigated for different injection intervals. The experimental results showed that when the injection interval of using the projectile is shorter then the deposit rate reduces and asymptotic fouling resistance would be decreased compared with the longer injection intervals. In the course of fouling process of anhydrous calcium sulfate, the sintering phenomenon may occur when the surface temperature changes from 85°C to 102°C which takes between 4 to 6 h depending on the fluid velocity and salt concentration. This may lead to hardened deposit layer thus the injection of projectiles may no longer effective to dislodge the deposit layer.

*Keywords:* Heat exchanger fouling; Deposition; Mitigation; Projectile

## 1. Introduction

Deposition of unwanted materials, commonly with low thermal conductivity, on the surface of heat exchangers constitutes a chronic industrial problem that may severely compromise thermal efficiency and environment. It occurs in many industrial processes including desalination units, cooling water services, chemical plants, and power plants. Two methods of i) on-line and ii) off-line are widely used to combat fouling of heat exchangers. In off-line approaches, the heat transfer device should be taken out of operation before attempting clean-up process. This would provide opportunity to conduct other services and also to attempt out most possible cleaning. On the contrary, in on-line approaches, the heat transfer device would continuously be cleaned without disruption of its operation. In fact, the main goal in on-line methods is to maintain heat transfer at an acceptable thermal performance level through partial, or ideally utter cleaning, without getting the exchanger out of operation.

In Fig. 1, different on-line methods are presented which can be divided into five groups. The first group is associated with the methods which, for instance, by changing the operating conditions such as feed dilution or filtration of heavy components from the feed, try to mitigate deposit formation. The other category is related to the chemical inhibitors which, depending on the type of fouling, may consist of various combinations. While using this method, it should be taken into consideration not to use toxic and corrosive substances as well as those substances that cause environmental pollution. The other group consists of several mechanical methods that according to their characteristics, they can profoundly reduce deposit formation. The advantage of these methods includes their controllability and much less environmental hazards.

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*Corresponding author.

Before attempting any of these mitigation methods, it is required to revamp the design of heat exchanger to discern if this stage is enough to reduce deposit formation. For instance, in plate heat exchangers, by increasing flow agitation, i.e. turbulence, or reduction of surface temperature, the possibility of deposition could potentially be reduced. Such exchangers include scraped-surface heat exchangers or the fluidized bed exchangers [1]. Generally, in design of heat exchangers, it is possible to postpone the conditions of deposit formation by taking the following steps into consideration:

- Selection of the correct type and size of heat exchanger
- Optimum operational conditions that cause fouling mitigation in the heat exchanger
- Modification the system design and the velocity of flow in the heat exchanger, to avoid any hot spots, the crossing flow and dead zones
- Design of a suitable exchanger for effortless cleaning of deposits

However, no matter how perfect and flawless the design of the heat exchanger is, the amount of the fouling may increase through changes in the process conditions. At this point, it is required to follow methods of fouling mitigation.

One of the most effective methods applied for fouling mitigation is to use projectiles in shell and tube heat exchangers which are still the most commonly used exchangers in industry. The method, as stated in Fig. 1, is one of the mechanical approaches to mitigate fouling. Mechanical methods have the advantage that they can be controlled and worked with easier. The efficiency of this method is determined depending on the type of deposition and heat exchanger, the deposition intensity of the exchanger and the deposition rate [1]. Projectiles of different types (see Fig. 2) can be classified in terms of type, size and the amount of shear stress they exert on the fouled surface. For example, sponge balls moving inside the heat exchanger's tubes can reduce fouling even in the early stage of deposit formation. The timing of using the projectiles depends on the intensity of deposition as well as the strength of the interaction between the cleaning projectiles and deposition [2–4]. Using the projectiles can be considered as one of the online techniques fouling mitigation but their utilization in aqueous environments is limited to temperatures below 120°C [3–5]. Furthermore, it is possible that restrictions such as chemical incompatibility with the working fluid would cause some problems in the course of operation.

Malayeri and Jalalirad [6] used seven different types of projectiles and it has been observed that sponge balls are more efficient compared to relatively much harder rubber balls. They also found that projectiles would be efficient, as long as the projectile diameter is a slightly larger than the inner diameter of heat exchanger tubes. In cases of using projectiles with the exact outer diameter equal to the inner diameter of the exchanger tube, their performance dropped dramatically. Malayeri and Jalalirad [7] in another study used two different projectiles with different sizes and hardness to remove calcium sulfate deposits. They observed that sediment removal was accomplished when a significant shearing force was exerted on the fouled surface by the projectile. In this case, the rate of deposit removal overcomes the rate of deposit formation. They also found that harder projectiles with larger contact areas are more effective compared to the smaller and softer projectiles. More experimental studies are required to get better insight into various aspects of using projectiles such as impact of injection intervals on removal of deposits as well as conditions under which the deposition reaches an asymptote. The present study is intended to address these questions.

## 2. Experimental set-up and procedure

The full description of the projectile test facility can be found elsewhere [2,3] and here it is only briefly discussed for the sake of brevity. Fig. 3 presents a schematic of the test facility which was able to use projectiles to combat deposition at different injection intervals and for various projectiles. The foulant was calcium sulfate which was obtained by adding calcium nitrate, tetra hydrate and sodium sulfate solutions in a storage tank of 60 L. Fig. 4 also provides a photo of the test facility. In order to perform the experiments, the bulk temperature must be set at a temperature of 40°C with the help of three jacket heaters around the supply tank. In addition, the supply tank is also equipped with a water cooling system to lower the bulk temperature should it exceeds a set temperature, here 40°C.

After the supply tank, a centrifugal pump (see [1] in Fig. 4) was used to flow the working fluid (calcium sulfate

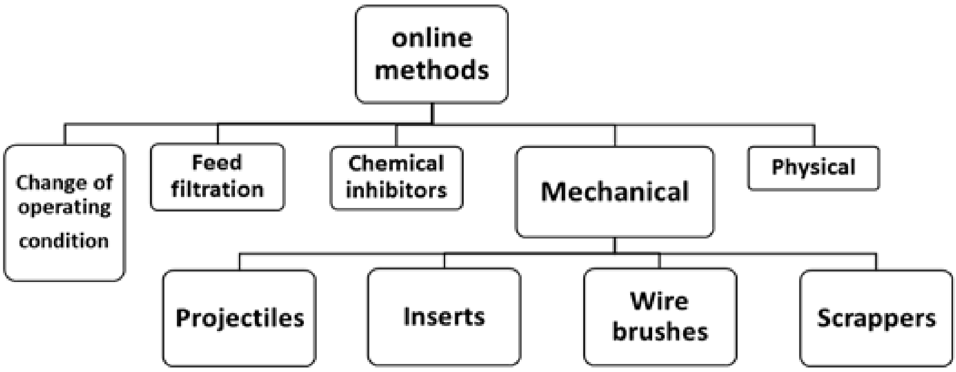

Fig. 1. Categorization of on-line mitigation methods [1].

*Soft projectiles*

| | | | |
|---|---|---|---|
| Code | P01 | P02 | P05 |
| Diameter (mm) | 21 | 22 | 24 |
| Type | Sponge-ball | Sponge-ball | Sponge-ball |
| Stiffness (N/% def.) | 0.178 | 0.558 | |
| $\tau_{dyn}$(kPa) | 14.2 | 75.0 | 80.1 |

*Hard projectiles*

| | | | | |
|---|---|---|---|---|
| Code | P04 | EX06 | P11 | P12 |
| Diameter (mm) | 19.8 | 19.8 | 20.0 | 20.2 |
| Type | Rubber-ball<br>Smooth surface | Rubber-ball<br>Smooth surface | Rubber-ball<br>Smooth surface | Rubber-ball<br>Smooth surface |
| Stiffness (N/% def.) | 1.040 | 1.040 | 1.040 | 1.040 |
| $\tau_{dyn}$(kPa) | loose | loose | negligible | 932 |

Fig. 2. Properties of hard and soft projectiles.

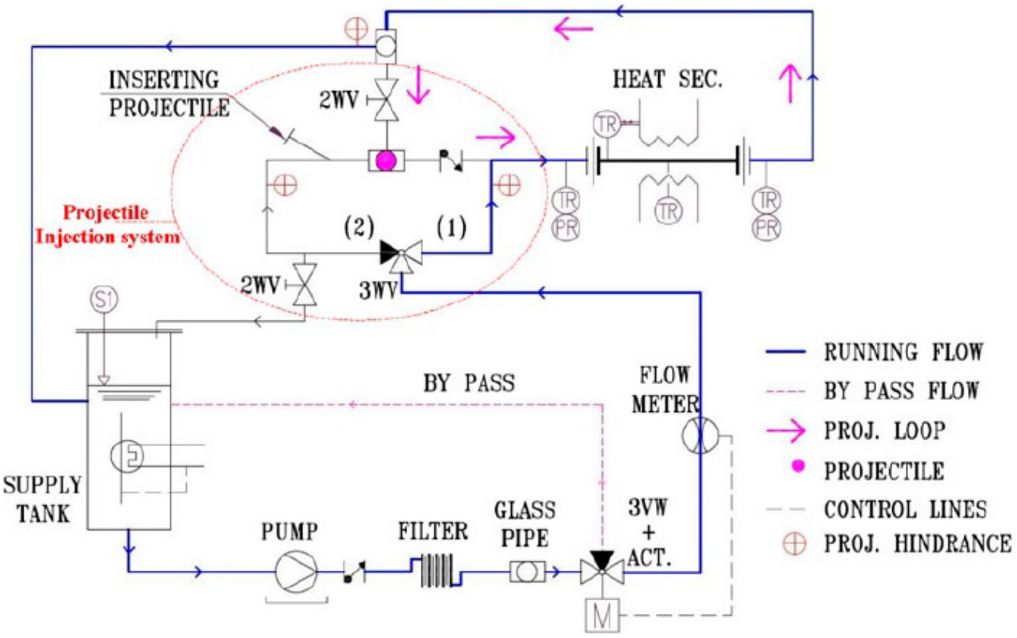

Fig. 3. Schematic of experiment set-up.

solution) to the heated section. After the pump, a filter was also placed to remove any solid particles or sediments from the incoming fluid. The fluid flow rate was adjusted using a magnetic flow meter and a three-way valve. In this procedure, the flow was measured by the magnetic flow meter (see [3] in Fig. 4) and then compared with the set value. If the working flow rate was greater than the set value then the fluid was returned to the supply tank as a back flow via the three-way valve. The heated section included a cylindrical tube which was heated by a 10 kW heater (see [4] in Fig. 4). The provided heat firstly passed through a stainless steel tube (grade 316) and then to the working fluid (calcium sulfate solution).

Two K-type thermocouples were embedded in the tube wall for measuring the surface temperature with the help of Wilson plot. The bulk temperature was also mea-

Fig. 4. A photo of the test facility which included: 1) centrifugal pump, 2) supply tank, 3) flow meter, 4) heater, 5) filter, 6) heated section and 7) heater control panel.

sured before and after the heated section. The projectile, as indicated in Fig. 4, entered the tube from a diagonal tube and pushed inside the tube by the help of incoming flow and finally passed through the heated section through the three-way valve (track 2 indicated in Fig. 4). After passing through the tube, the projectile returned to its initial position for the next injection through a two-way valve.

## 3. Data reduction and governing equations

In general, the deposit formation on heat transfer surfaces is influenced by two counteracting processes of deposition and removal which may occur simultaneously. In order to determine the rates of deposition and removal, in turn, a model is required which should include these two rates. Thus, the net rate of fouling is the result of difference between the deposit formation and removal which can be defined as:

$$\frac{dm_f}{dt} = m_d - m_r \tag{1}$$

In this equation, $m_f$ is the rate of the accumulated mass of deposit on the surface, $m_d$ is the deposition rate in heat-transfer surface and $m_r$ is the fouling removal rate. Eq. (1) can be rewritten as:

$$\rho_f \lambda_f \frac{dR_f}{dt} = m_d - m_r \tag{2}$$

where in this equation, $\rho_f$ and $\lambda_f$ denote the density and thermal conductivity of the deposit, respectively.

$$R_f = \frac{1}{U_f} - \frac{1}{U_c} \tag{3}$$

In this equation, $R_f$ donates to fouling resistance and $U_f$ and $U_c$ are overall heat transfer coefficients under fouling and clean conditions, respectively. To find the deposition rate, it is required to know the deposition mechanism on the investigated heat transfer surface. The deposition mechanism for the calcium sulfate is crystallization. Therefore one has to find the governing equations for the transfer of particles from the fluid to the surface. Having considered that both processes of mass transfer and reaction would be responsible for the accumulation of unwanted materials during crystallization fouling on the surface then the following equation can be used for mass transfer:

$$m_t = \beta\left(C_b - C_s\right) \tag{4}$$

where $m_t$ is the mass which moves from the fluid to the fluid-surface interface. $C_b$ is the concentration of calcium sulfate in the bulk and $C_s$ is the saturated concentration of calcium sulfate and finally $\beta$ is the mass transfer coefficient.

On the other hand, the calcium and sulfate ions transferred to the surface form calcium sulfate crystals through a chemical reaction and stick to the surface. Mass flow rate of the reaction and the formation of the particles crystal can be demonstrated through the following equation [8]:

$$m_a = k_r\left(C_s - C_i\right)^2 \tag{5}$$

Here, $m_a$ is the mass accumulation rate on the heat transfer surface; $C_i$ is the concentration of calcium sulfate at the interface; and $K_r$ is the reaction constant. In order to provide an equation for the deposition rate with consideration that $C_s$ can be omitted from these equations, then it can be drawn that [8]:

$$md = \beta\left[\frac{1}{2}\left(\frac{\beta}{K_r}\right) + \left(C_b - C_i\right) - \sqrt{\frac{1}{4}\left(\frac{\beta}{K_r}\right)^2 + \left(\frac{\beta}{K_r}\right)\left(C_b - C_i\right)}\right] \tag{6}$$

## 4. Results and discussion

### 4.1. Deposition rate

The deposition rate is, in principle, the amount of mass which is accumulated per unit area per unit time. In order to probe the changes of deposition on heat transfer surface, the steps of this process should carefully be evaluated. In general, the deposition of heat transfer surface includes three major steps when fouling resistance approaches an asymptote, namely, i) induction, ii) transition and iii) asymptotic. Fig. 5 shows a schematic of these three steps for projectile P02 (refer to Fig. 2 for more details). The induction period, as the first step of deposition, is when the first crystal nucleus would be adhered onto the surface. The deposition rate during this period is approximately zero. This is because at this stage the fine particles of calcium sulfate which move to the surface, would initially roughen the surface and increase turbulence on the surface. Therefore, the amount of local heat transfer coefficient increases. Transition begins immediately after the induction. In fact, nucleation that is formed and completed in the induction period, begins to spread and form crystals of calcium sulfate. At this stage, the maximum rate of deposition and also the maximum rate of deposit formation occurs. Since the use of projectiles takes place in the course of operation, fouling removal simultaneously begins with deposit forma-

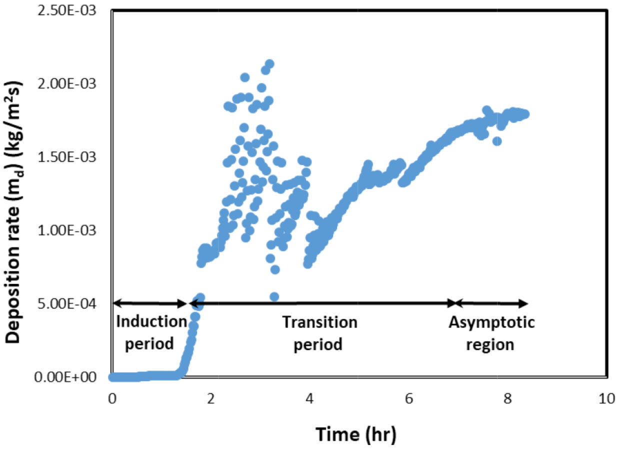

Fig. 5. Changes of deposition rate vs. time, for injection interval of 1 inj/5 min, bulk temperature 40°C, bulk concentration 4.6 g/l, projectile P02.

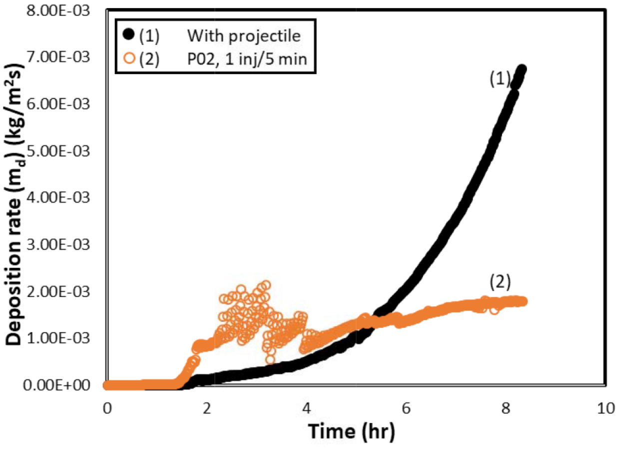

Fig. 6. Changes of deposition rate vs. time at 1 inj/5 min and without projectile, bulk temperature 40°C, and bulk concentration of 4.6 g/L, projectile P02.

tion and therefore during this time, one would also see the maximum rate of removing fouling. Asymptotic is the last step of the deposition process during which the changes in deposition and removal rates would either be diminished or the deposit layer is too hard to be dislodged.

The utilization of projectiles for fouling mitigation would profoundly affect the deposition rate. Over time as the projectile passes through the heat exchanger section, the deposit gets more compact, harder and thus less porous. Moreover, the use of projectiles would reduce the duration of the induction period and the shorter projectile injection interval would result in shorter duration of the induction. This is because when a projectile pushes its way through the tube due to surface contact, the projectile creates a rough surface which facilitates deposit formation. In fact, the projectile would initially accelerate deposit formation on the surface resulting in shorter induction time. This reduction may somewhat depend on the type, material and size of the projectile. The further that a projectile increases the surface roughness, the induction period becomes shorter and the deposition starts in a shorter time from the beginning of the process. In the absence of projectiles though, the induction period will be much longer, on one hand when the projectile tube is injected every 5 min, induction period lasts 1.37 h, on the other without the projectile this time is 2.35 (see Fig. 6). In addition, shorter injection intervals would result in shorter induction period. This is because shorter injection intervals increase the surface roughness thus more calcium sulfate is expected to form on the surface.

As time goes on, the deposit layer would continuously become thicker but the opposite would be expected as soon as the projectile enters the tube. In Fig. 6, the deposition rate is presented versus time for an injection interval of every five minutes. It is obvious that after the induction stage, the rate and amount of deposition is increased. After almost three hours from the start of the experiment, the rate of deposition reaches its highest value of 0.0021 kg/m$^2$ s. During the transition stage though, the deposition is characterized with fluctuations and discontinuities. The sudden change in fouling resistance as well as rate of deposit is due to deposit removal by the projectile. Following the deposition process, it can be seen that the process is gradually reduced and meanwhile the deposit rate decreases. In this case, the deposition process becomes too slow after 4 h of operation.

Once the transition is ended then the fouling process enters the asymptotic stage. In the course of this stage, the driving force (temperature gradient) for deposition decreases and instead the removal gets somewhat higher due to the reduction of flow passage. Having said though, given that the surface temperature increases during the process, sintering phenomenon may occur during tube, in which deposit removal is practically impossible.

In general, all three stages of deposition in different intervals of using projectiles (such as intervals of every 2, 5, 10, 15 and 30 min) are significant, but it is the injection interval that affects rate and expansion of deposition. If the projectile is injected every 2 min compared to 10 min then it can reduce fouling layer as well as deposit thickness. In this case, the maximum deposit rate is less than the one for longer intervals, but the factor which contributes to comparison of projectile performance in different injection intervals as well as the influence of various projectiles is the asymptotic value of fouling resistance. Actually if the projectile exerts enough shear stress and sufficient contact with the surface, then the asymptotic value decreases and this indicates a better performance of projectile. In the present study, P02 projectile is used which is 10% larger than the internal diameter of the tube inner diameter. The surface contact and shear stress exerted by P02 on the surface is much higher than other sponge or rubber projectiles [9]. This is because Malayeri and Jalalirad [9] showed that the cleaning action of projectiles is dependent upon their stiffness as well as the projectile's contact area with the tube surface. They called it contact stability (or Z factor) which is a function of hydrodynamic and dynamic forces. They also showed that hard projectiles exert a much higher dynamic shear force than the soft projectiles. Nonetheless, under the propulsion force of flow, they do not exert a remarkable shear due to unstable contact between the projectiles and the tube. Accordingly, the cleaning performance of hard projectiles is not noticeably better than the softer ones. The dimensionless contact stability or "Z factor," is reported to change from 0.2 for the hard projectiles and between 0.6 to 0.9 for the soft projectiles. For the P02 projectiles which is used in this study, the Z factor is 0.9 which shows a good combination of shear stress exerted by the projectile as well as its contact area while passing through the tube.

The projectile is tested at different intervals and the results of its injection are shown in Fig. 7. In general, the shorter the time of projectile injection, a more reduction of deposit layer is expected. As can be seen in Fig. 7, when the projectile is used in an interval of 2 min, the asymptotic value is equal to $1.07 \times 10^{-3}$ kg/m$^2$s, where this value equals to $1.90 \times 10^{-3}$ kg/m$^2$s when the projectile is injected every 10 min. It can be seen that this value is much lower for the 2-min mode than the time when the projectile is used every 10 min. For the longest injection interval of 30 min, the asymptotic value equals $7.5 \times 10^{-3}$ kg/m$^2$s. In general, as it can be seen in Fig. 7, in the course of using projectiles, a similar trend can be seen in all the intervals. At first, during the induction stage and then the transition, the deposition rate continually increases during which it reaches its maximum value. The deposition rate would then decreases gradually before reaching a steady state or an asymptote. As mentioned earlier, the shorter the injection interval is, the less the deposit rate will be and the opportunity to expand the sediment layer becomes lower. For a state that the system is without a projectile, it is observed that after the induction period which has a longer period compared to that with projectile, the deposit rate increases. Nonetheless, as it can be seen in Fig. 7, in case of using no projectile, the process demonstrates an asymptotic behavior and follows an increased continuous trend. Therefore, as long as the operational circumstances allow, the fouling run continues, but after a certain point it is not possible to continue testing due to excessive surface temperature thus the fouling run should be terminated.

### 4.2. Removal rate

The trend of changes in the process of removing precursors from the surface is similar to the deposition process. In the removal process, at the beginning of the experiment (induction period) due to absence of deposit, the rate of removal is zero or slightly greater than zero. Once the induction period elapsed, as the deposit process begins, simultaneously the removal process begins (transition stage). At this state, the process of removal is similar to the process of deposition and changes in removal are taken place rapidly due to increased deposition. At the end, like the deposition stage, the removal process also reaches the asymptotic value. What is important between these two processes is that in the process of deposition, the aim is to achieve the lowest amount of deposition over time whereas in the process of removal, is to achieve the highest rate as a function of time. In fact two processes are similar but in the opposite direction of each other.

In Fig. 8, the removal rate for an injection interval per 2 min is shown. At first, the process follows a fixed trend and over time after 1.3 h of operation, it begins to change. Furthermore, after three hours of operation it reaches the highest amount of removal. As it can be seen, the process then levels off and finally after five hours, it reaches almost an asymptote. For other injection intervals, the same trend is observed and the difference between intervals is mainly reflected in the extent of the induction period as such that longer the injection interval, longer would be the duration of induction period. It is noteworthy that the shorter the injection interval would be a shorter transition period would be expected. For example, the transition period 1 inj/2 min is approximately 5.45 h before the fouling reaches an asymptote. For an injection interval of 1 inj/5 min also the transitional period would be equal to 5.76 h and for a maximum interval of 1 inj/30 min, this takes about 7.1 h. For the asymptotic region, it is shown that the smaller injection intervals correspond to lower asymptotic fouling.

The asymptotic fouling value is an important and efficient factor in removal rate in order to compare the performance of P02 projectile at different injection intervals. In Fig. 9, the removal rate is presented as a function of time for intervals of 1 inj/2, 10, 15, and 30 min as well as those without using projectiles are shown. The asymptotic value for 1 inj/2 min reaches –0.06602 kg/m$^2$s in about 8 h after

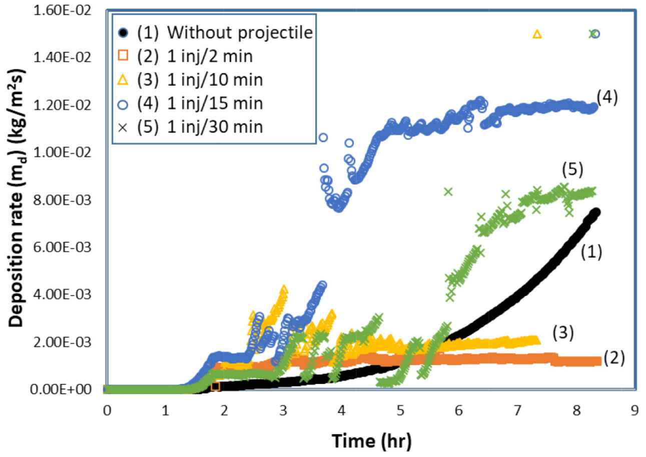

Fig. 7. Deposition rate (kg/m$^2$s) vs. time (h) for injection intervals of every 2, 10, 15, 30 min and without projectile, bulk concentration 4.6 (g/L), bulk temperature 40°C, Projectile P02.

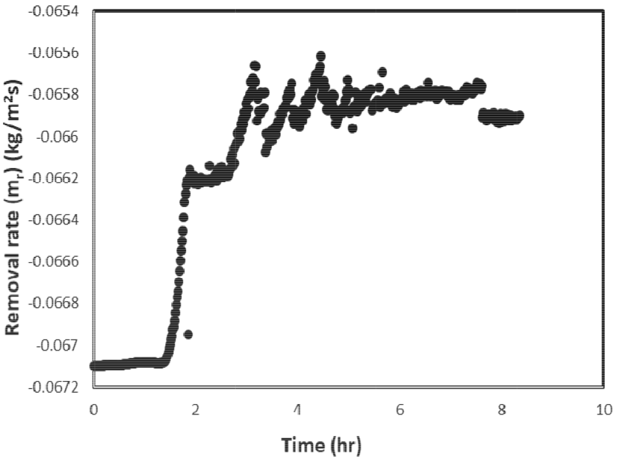

Fig. 8. Changes of removal rate vs. time at 1inj/2min, bulk temperature of 40°C, and bulk concentration of 4.6 g/L, Projectile P02.

the start of fouling run and for 1 inj/10 min it is –0.11738 Kg/ m$^2$s. It can be observed that the removal rate for 1 inj/2 min is approximately 44% more than that for 1 inj/10 min.

It is worthwhile to mention in Fig. 9, is that the removal rate is negative. This can be related to the fact that the removal rate becomes negative when the deposition rate is smaller than the changes in fouling layer over time. In other words, according to Eq. (1), $m_r$ becomes negative only when $m_d > \frac{dmf}{dt}$. Which means that changes in deposit over time gets greater than the deposition rate and therefore implies that the amount of removal is greater than deposition rate. Surprisingly, the efficiency of fouling mitigation is better with one injection every 30 min when compared to one every 15 min. Experiments with longer injection intervals e.g. every 15 and 30 min had poor reproducibility. Hence for long intervals the effect of cleaning by projectiles diminishes and other mechanisms take over to make the results more unpredictable. indicates that 1 inj./10 min would be an optimum interval to keep the tube at an acceptable level of cleanliness, about one fifth of that without injection.

### 4.3. Impact of sintering

One of the main reasons for the asymptotic behavior of deposition is sintering. During this phenomenon, the fouling structure changes into a non-porous and hard structure from a crystalline and porous shape. If the temperature of the deposit layer is higher than the minimum sintering temperature, then the deposit would partially melt. The minimum sintering temperature (MST) usually changes between 2/3 and 4/5 of the melting point of the ingredients of the fouling layer [2,3]. The deposit layer is anhydrous calcium sulfate, which has a melting point of about 401 K (128°C). Therefore, the MST range falls in the range of 358 K (85°C) > MST > 357 K (102°C).

For the deposit layer, the part near the tube wall which is in contact with the heat source (outer layer), has a higher temperature than a part of fouling part which is in contact with the solution (inner layer). Therefore, the inner layer of fouling that is in contact with the solution and has a lower temperature would have a porous and crystalline structure and the outer layer that is in contact with high temperature has a harder and non-porous structure than the inner layer. If the temperature of the outer layer exceeds the MST and goes further it will sintered and the outer layer of fouling becomes hard and non-porous. The harder and non-porous the deposit layer that would be, the lower becomes the removal rate. If the deposit layer gets harder continuously then it is no longer possible to remove the deposit even if the projectile is injected at shorter injection intervals. This is because the occurrence of sintering would change the structure of deposit layer from non-porous close to the wall to porous close to the solution [2].

In the course of projectile injection, for the injection interval of 1 inj/2 min, the removal rate increases and the thickness of the internal part of the fouling layer is expected to reduce. Consequently, the occurrence of sintering would be minimal. For interval injection of 1 inj/15 min or 1 inj/30 min though, the thickness of the internal part of the deposit layer increases and the time necessary to reach the temperature required for sintering would be available thus the deposit layer becomes hard and non-porous.

In Fig. 10, for 1 inj/2 min, for a surface temperature of 358 K (85°C), the process is almost at the beginning of the transition process. At an inner surface temperature of 375 K (102°C) the diagram has almost reached the asymptotic stage and from that temperature on the next layer becomes gradually harder and non-porous. In fact, in the asymptotic region, the crystalline and porous deposit layer is reduced (for 1 inj/2 min) and the remaining deposit layer would become hard and non-porous which takes between 4 to 6 h depending on the fluid velocity and salt concentration. Under such circumstances, the formation of new crystals on the already hardened layer is no longer possible and the deposition process becomes constant. On the contrary, the projectile would not exert enough shear stress to dislodge the deposit from the hard and non-porous layer. Also, in 1 inj/10 min is both the upper and lower MST in the transition range. This means that before they reach the asymptotic region, they are gradually being sintered and the fouling layer changes into a hard and non-porous from crystalline

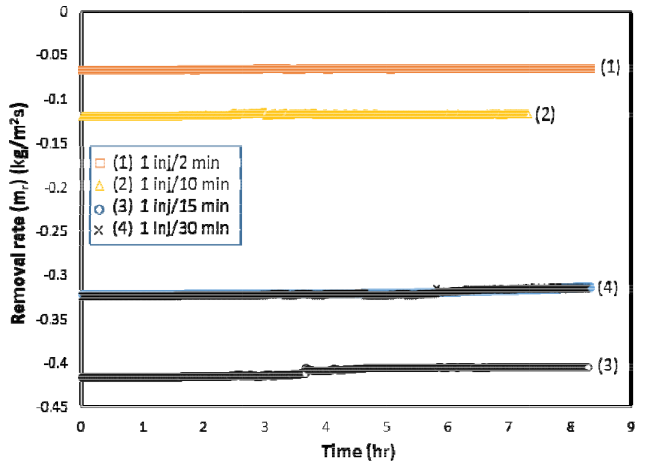

Fig. 9. Changes of removal rate vs. time for injection intervals of 1 inj/2, 5, 10, 15, 30 min and without projectile, bulk concentration 4.6 g/L, bulk temperature 40°C, Projectile P02.

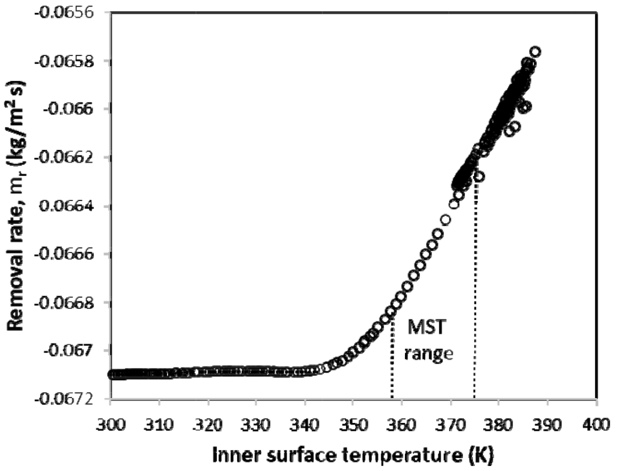

Fig. 10. Changes in minimum sintering temperature (MST) for the 1 inj/2 min, bulk concentration 4.6 g/L, bulk temperature 40°C, Projectile P02.

state. Therefore, at temperatures above 375 K (102°C) the deposit layer gradually becomes harder and non-porous and the cleaning operations become more difficult.

## 5. Conclusions

The utilization of projectiles for fouling mitigation would be efficient as long as they can exert enough shear to dislodge the deposit layer. The approach is also on-line thus there is no need to shut down the exchanger. The method would particularly be robust if applied from the beginning of the operation. Thus if the surface is already fouled with deposit, then the projectiles will no longer be able to spall off the deposit layer. The P02 projectile used in this study was soft and spongy with a diameter 10% larger than the inner diameter of the tube. In comparison to other projectiles of the same type and the rubber projectiles, the projectile shows a better ability to remove deposits. That is mainly due to effective surface contact and shear stress which the projectile would have with the surface. The present projectile was also investigated at different injection intervals and it was observed that the shorter the interval, the efficiency of projectile to remove deposit would be higher. There would be through a trade-off between the optimum injection interval and sintering phenomenon that would occur which otherwise would harden the deposit layer.

## Symbols

$C_b$ — Bulk concentration (g/L)
$C_i$ — Calcium sulfate concentration at liquid-surface interface (g/L)
$C_s$ — Saturated calcium sulfate concentration (g/L)
$C^*$ — Calcium sulfate concentration at inner surface temperature (g/L)
$K_r$ — Reaction constant ($m^4$/kg·min)
$m_a$ — Adhered mass flux on heat transfer surface (kg/$m^2$s)
$m_d$ — Deposit mass flux (kg/$m^2$s)
$m_f$ — Accumulated mass flux (kg/$m^2$s)
$m_r$ — Removal mass flux (kg/$m^2$s)
$m_t$ — Mass transferred flux to heat transfer surface (kg/$m^2$s)
$R_f$ — Thermal fouling resistance ($m^2$K/W)
$U_c$ — Overall heat transfer coefficient at clean condition (W/$m^2$K)
$U_f$ — Overall heat transfer coefficient at clean condition (W/$m^2$K)
$b$ — Mass transfer coefficient (m/s)
$l_f$ — Fouling thermal conductivity (W/$m^2$K)
$r_f$ — Density of fouling layer (kg/$m^3$)

## Subscripts

b — Bulk
a — Adhere
d — Deposit
f — Fouling
i — Interface
r — Removal
s — Saturated
t — Transfer

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