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Online cleaning of tubular heat exchangers in water service systems using projectiles

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ABSTRACT

In water service processes, tubular heat exchangers are commonly used to provide a heat transfer medium for cooling or heating of which both are subject to fouling of heat transfer surfaces. The deposit would dominantly build up in form of biofouling, crystallization, and/or particulate fouling depending on the operating and surface conditions. This, in turn, may result in more demand for excessive energy consumption due to higher pumping requirements, as well as for offsetting the impact of fouling. In this study, as part of a European project entitled “Clean-Ex,” a comprehensive set of experimental runs was carried out for crystallization fouling of $CaSO_4$ with and without projectiles. Due to laboratory restriction, the fouling runs were performed at accelerated conditions to rigorously characterize the impact of projectile cleaning in terms of injection frequencies and various types of projectiles. The experimental results show that cleaning by using projectiles will only take place when no deposit is allowed to form on the surface or if formed, then it is just brittle; hence, the projectiles can remove it due to excessive shear forces. There is also a direct link between the rate of fouling and injection frequencies.

Keywords: Fouling; Heat exchanger; Desalination; Mitigation; Cleaning

1. Introduction

Heat exchangers have a crucial and widespread application in many industries. Thus, not surprisingly, their design, operation and maintenance are of prime importance. Among many dominant considerations, one large element of uncertainty in their operation is the formation of deposits on heat transfer surfaces. The deposits are largely due to the presence of precursors in the process fluid which may adhere to the surface or assisted when corrosion takes place. The occurrence of fouling causes heat exchangers to be usually overdesigned in order to reach desired performance. In addition, pumps are also oversized to compensate increased pressure drop resulting from a reduced flow area due to deposition. Therefore, efficient mitigation and cleaning methods must be available to safeguard the operation of heat exchangers.

Projectiles of different shapes, for example sponge balls, can be propelled through the heat exchanger tubes to remove deposits already during the early stage of formation. The frequency and duration of application depends on the severity of fouling and the

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strength of interaction between cleaning projectile and deposit. Typically, projectile online cleaning techniques are limited to aqueous systems at temperatures below about 120˚C, due to the stability of the projectile material. There may also be some limitations due to chemical incompatibility. If the application of cleaning projectiles to individual tubes occurs at random (i.e. in sponge ball systems), this may lead to over- and under-cleaning of tubes depending on their location in the tube bundle. The advantages of this method are that they can effectively mitigate fouling thus provide stable operation. The projectiles must also be replaced regularly as they may wear out after their life expectancy is expired.

Although projectiles have been used in the past few decades, nonetheless, the experimental results are scarce in the open literatures. A few reported results in the literature are those that were obtained from mostly desalination plants [1,2]. There are many unanswered questions that need addressing such as optimum injection frequency, minimum required shear force to remove fouling layer, applicability of projectiles at elevated temperatures and minimum required velocity for the propulsion of the projectiles inside the pipe, random distribution of cleaning balls in different densities of projectiles and flow conditions.

In this study, a comprehensive set of experimental runs is performed for crystallization fouling of $CaSO_4$ with and without projectiles. The test rig contains a single hot tube where deposit formation can take place under controlled operating conditions and the facility for injecting the projectiles in different intervals. Accordingly, the objectives of this investigation are to discern the rate of deposit formation and impact of projectile injection on cleaning. Furthermore, the optimum injection frequencies in different fouling rates and different types of projectiles are also investigated.

2. Experimental set-up

A test rig was designed and constructed to simulate conditions under which fouling in water service processes would occur. The rig includes an online cleaning device which enables introduction of projectiles for various operating scenarios including (i) continuous or (ii) injection of projectiles in different time intervals. The projectiles pass through a single tube where the part in middle is heated up for investigating fouling inside the pipe. The picture of the test rig is presented in Fig. 1. The projectile can be injected into a heated tube by turning the flow through a three-way valve “3WV”. After passing the heating zone, the projectile will be recirculated to a transparent part (see far left side in Fig. 1) to

Fig. 1. Fouling test rig equipped with projectile injection system.

confirm that it is not stuck anywhere in the rig. Thereafter by opening a two-way valve “2WV”, a small flow brings the projectile to its first position for the next injection.

The flow rate is controlled by a “flow meter” and “3WV+ actuator”. The flow meter sends signals to the actuator to allow a certain flow passes through the valve. Excessive flow returns back to the tank through a bypass line.

The supply tank is equipped with a cooling coil and three jacket heaters, each with a power of 500 W (1,500 W) to adjust the bulk temperature of solution to a certain value which is 40˚C in this study. The inner diameter of the heated pipe is 20 mm and was made from stainless steel 316. The inner diameter of tube was considered similar to the majority of those in operation in industry. The intended operating conditions are listed in Table 1.

For monitoring fouling inside the tube, two thermocouples were mounted in the wall of the pipe. The Wilson test was then used to determine the surface temperature of the pipe. To do so, two holes were machined to accommodate two K-type thermocouples with a diameter 0.5 mm inside the wall of pipe.

Table 1
Operating conditions

Variables	Range
Bulk temperature	40˚C
Velocity	0.5–3.5 m/s
Chemicals	$CaSO_4$
Maximum surface temperature of tube	135˚C
Inner diameter of tube	20.0 mm
Minimum projectile injection interval	2.5 inj./min
Maximum heat flux	570 kW/m^2

Table 2
Specifications of used projectiles

Projectile			
Code	P01	P02	P04
Diameter (mm)	21	22	20
Type	Sponge ball	Sponge ball	Rubber ball, smooth surface
Stiffness	Flexible, soft	Flexible, hard	Less flexible (rigid)

2.1. Specifications of projectiles

Three types of projectiles are used in this investigation as specified in Table 2. The projectiles are all spherical shape but differ in size, stiffness and surface texture. The harder and larger the projectiles that are the more efficient cleaning is expected as then they need to produce enough shears to remove deposit after nucleation. Projectile P01 has a 5% bigger than inner diameter of pipe and soft just enough to wipe out any initial nucleated crystal. P02 was 10% bigger and harder to produce more shears to remove deposit when the fouling rate is relatively high. P04 was a rigid type with similar diameter of the inner diameter of pipe.

2.2. Chemical preparation

Calcium sulphate is used as foulant which has an inverse solubility with temperature above 40°C. This solubility is strongly a function of the presence of other ions; thus, demineralized water with a conductivity of 50 μS/cm is used. Since calcium sulphate crystals do not dissolve easily in water thus calcium nitrate tetrahydrate ($Ca(NO_3)_2{\cdot}4H_2O$) and sodium sulphate (Na_2SO_4) were dissolved in water to produce calcium sulphate crystallizing on inner hot surface of the pipe [3].

The volume of supply tank was 60 L, and thus, at the start of each run, the test rig was run just with 30 L demineralized water, and once in steady state, two 15 L volumes of high-concentrated calcium nitrate tetrahydrate and sodium sulphate were added to the supply tank. The two solutions are then mixed immediately due to high turbulence in the supply tank.

Fifteen litres of calcium nitrate tetrahydrate and 15 L sodium sulphate solutions are heated to 40°C in a separate thermostat tanks. A few minutes before the surface temperature reaches its set temperature, these two solutions are added into the supply tank. During the experiment, the concentration of $CaSO_4$ is measured by EDTA titration and controlled by addition of respective solutions. The titration is performed every half an hour. In the event of fouling, the concentration will initially decrease due to surface crystallization. To maintain its set value, more chemical with specified ratio will be added into the supply tank. For that purpose, a highly concentrated solution of calcium nitrate and sodium sulphate are added to the supply tank to maintain the desired bulk concentration.

2.3. Experimental procedure

At the beginning of each experiment, various components of the test rig, that is, supply tank, filter and heating zone, have to be checked to see whether there is any deposit left from the previous experiment. To maximize the lifetime of the furnace, the furnace temperature is set to increase at a rate of 10 K per minute. When the supply tank reaches a bulk temperature of 40°C, the temperature is controlled by a water-cooling system.

The flow velocity can be adjusted by a flow meter and a three-way valve plus actuator. After each experiment, the heated pipe, where deposit has taken place, is disassembled from the test rig and analysed. Photographs of the inner surface are taken to see the fouling layer in the heat section. The photographs would help to discern the texture and coverage of the deposit layer. Thereafter, the pipe will chemically be cleaned before using it for the next experiment. The washing chemical is inert and does not react with the surface, so the surface texture remains intact.

2.4. Data reduction

For the determination of heat transfer coefficient, data such as bulk temperature, output temperature, flow velocity and inner surface temperature are required. Inner surface temperature could be calculated using two inserted thermocouples in the middle of wall pipe. The exact positions of these thermocouples towards inner surface were calculated with Wilson plot test. By deviation of heat transfer coefficient during the time then the fouling curve could be plotted. The shape of fouling curves indicates the deposition trend and impact of projectile injections during the experiment. Despite the type of fouling is known to be calcium sulphate, it is not possible to specify the exact value of its thermal conductivity since it depends on many factors like its molecular structure or porosity. To characterize the deposition process, the fouling resistance R_f can be calculated according to the overall heat transfer coefficients at clean and fouling conditions.

$$R_f = \frac{1}{U_f} - \frac{1}{U_{cl}} \tag{1}$$

where U_f and U_{cl} are the overall heat transfer coefficients under fouling and clean conditions. U_f is measured from the following equations:

$$Q = A_i \cdot U_f \cdot (T_{si} - T_b) \tag{2}$$

$$Q = \dot{m} \cdot C_p \cdot (T_o - T_i) \tag{3}$$

It is important to point out that fouling spots on the tube surface have also a direct effect on the surface roughness; this roughness leads to a turbulence increase. Sometimes initially when the first crystals are formed in terms of additional roughness, the boundary layer may be agitated and thus the heat transfer is higher than clean conditions. As a result, a negative fouling resistance would be expected.

3. Results and discussion

Fouling experiments are initially performed without injecting projectiles under different operation conditions. The results can then be used to assess the performance of projectiles under similar operating conditions. Fig. 2 shows how would fouling resistance vary vs. for the two velocities of 0.8 and 2.2 m/s. As stated before, in this investigation, the diameter of pipe and the velocities are in order of magnitude of those in industry. As it can be seen for a higher velocity of 2.2 m/s, the rate of fouling is slower. A jump up after 5 h in curve of 0.8 m/s shows sometimes a bulk of particle could be pasted over the lower layer. Similarly, a jump down in curve of 2.2 m/s shows a

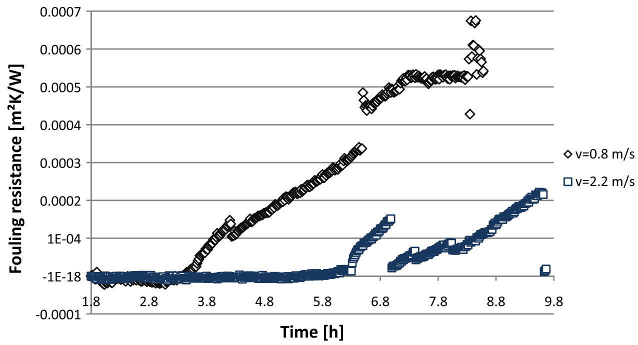

Fig. 2. Fouling resistance vs. time for different velocities without injecting projectiles. T_b = 40℃, T_{si} = 80℃ and C = 3.8 g/l.

part of deposit would be removed during the run even without injecting any projectile. Sudden and sharp drops of fouling resistance can be explained by the flow removing parts of the fouling layer. Contrariwise, an increase in fouling resistance is more difficult to explain, but reattachment of larger particles on the surface which were recirculating in the rig can be accounted for. Both occurrences can evidently be seen in this figure but sudden temperature rises in lower velocities is more probable as well as sudden temperature drops for higher velocities.

Fig. 3 shows the variation of fouling resistance vs. time for different concentrations of $CaSO_4$. At a concentration of 5.0 g/l, fouling is so severe that the test had to be terminated only after approximately 2 h to avoid the pipe to be burnt-out. With this concentration, no induction time was also experienced and the fouling rate is too large. The runs with concentrations of 3.0 and 3.5 g/l show no fouling during the time exposure of 8 h. At a concentration of 4.0 g/l, the fouling resistance starts to rise after 1 h of

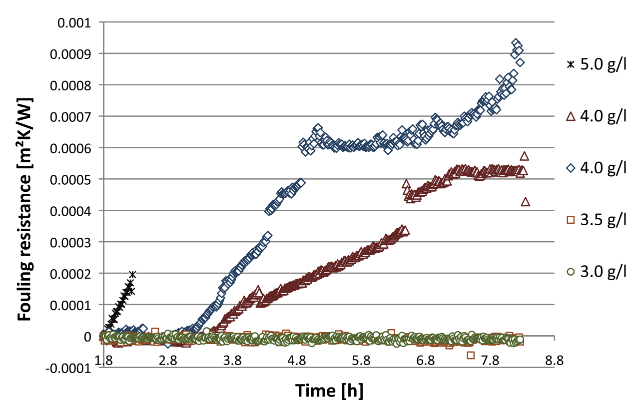

Fig. 3. Fouling resistance for different concentrations without injecting projectile. T_b = 40℃, T_{si} = 80℃, and v = 0.8 m/s.

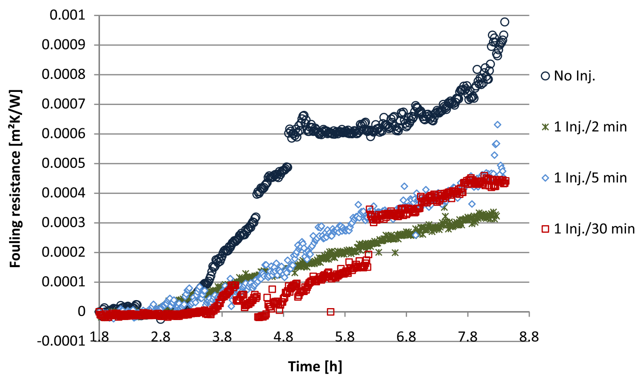

Fig. 4. Fouling resistance, projectile P01 at different time intervals. T_b = 40°C, T_{si} = 80°C and C = 3.8 g/l, and v = 0.8 m/s.

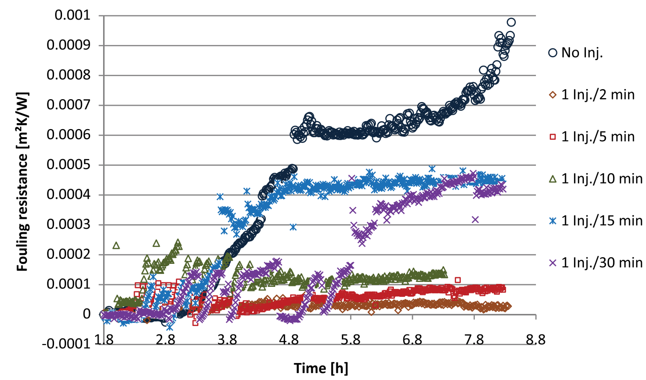

Fig. 5. Effect of P02 on cleaning in different injection frequencies. T_b = 40°C, T_{si} = 80°C and C = 3.8 g/l, and v = 0.8 m/s.

induction period. Two experiments with concentration of 4.0 g/l were carried to check the reproducibility. As expected, the fouling resistances do not match due to incorporation of too many parameters in micro and macro scales.

The first attempted projectile to mitigate fouling was P01. It consists of spongy material and was quite soft. Each projectile has a nominal diameter of 21 mm. The injections intervals were every 2, 5, and 30 min. In Fig. 4, the curves of the fouling resistance without and with injection are presented. Smaller injection intervals have better efficiency on mitigation of fouling. However, the pipe cannot be kept entirely free from deposit even with an interval of every two minutes. In this case, the fouling resistance is reduced to about a third of the value as without injection.

For projectile P02, the injection intervals were every 2, 5, 10, 15, and 30 min. The fouling resistances are shown in Fig. 5. Up to an interval of 1 inj./10 min, the pipe surface remains free from fouling during the test. For fewer injections, fouling can only be mitigated a few times, but after that, the fouling layer starts to grow. Contrariwise, the efficiency of fouling mitigation is better with one injection every 30 min when compared to one every 15 min. The reason for this trend is not immediately clear but more experimental work is needed before a firm conclusion can be drawn. Fig. 5 also shows 1 inj./10 min would be an optimum interval to keep the pipe in an acceptable level of cleaning about one-fifth compared with those without injection. It is still a question how this result would be comparable with industries scales. Nevertheless, considering this point that injection decreases the fouling factor one-fifth than without injection, the size of heat exchanger also would be smaller by 20% for the construction. Thus, it has a major compact system recovery, independent of duration of experiments and injection interval towards what exists in industry.

Not only the measurement of fouling resistance would dictates how effective the projectiles are at any specified injection interval but the fouled surface can also be examined after each run to see how fouling is developed. After each experiment, inside the pipe was fully scanned and the sketch of covered areas by deposit is prepared. Fig. 6 shows typical mappings of deposit after experiment with P02. Obviously, the lowest time interval of 1 inj./

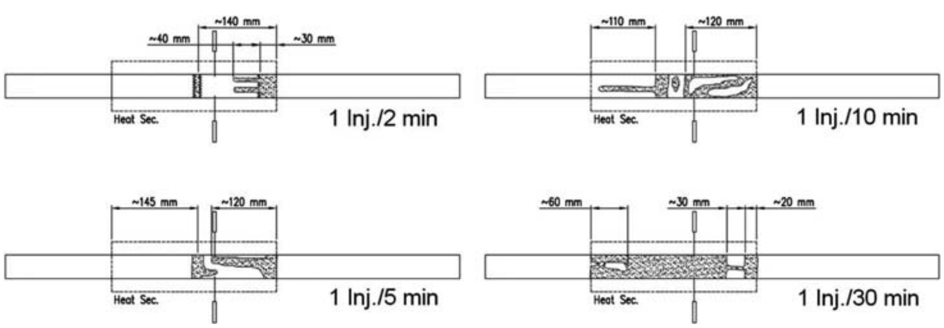

Fig. 6. Mapping of deposit layer for P02.

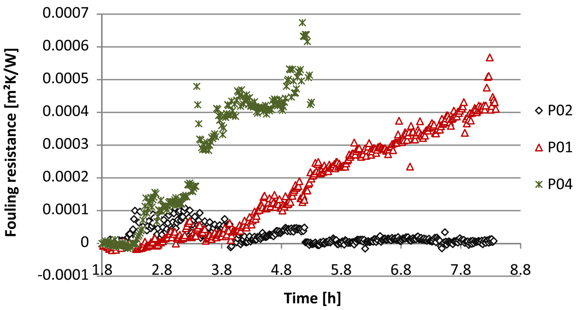

Fig. 7. Comparison of various projectiles on cleaning in same injection intervals. T_b = 40°C, T_{si} = 80°C and C = 3.8 g/l and injection interval in each 5 minutes, and v = 0.8 m/s.

2 min cleans the pipe the best, but the deposit cannot be completely removed. In longer injection interval, more deposits remain. With an interval of 1 inj./15 min, only parts of the fouling layer are removed. It is imperative to note for projectile P01 in all cases the deposit layer had fully covered the heating zone.

Apart from the comparisons a projectile in different injection intervals, the effectiveness of various projectiles are also compared together. Fig. 7 shows experimental results for the same operating conditions but with four different projectiles. The interval injection was 1 inj./5 min. P01 and P02 are sponge-type with the diameter bigger than the pipe, they are flexible to be deformed and passed through the pipe. P02 is harder and bigger than P01. The results show that P02 plays a better rule in keeping the surface cleaner than P01. P04 is a rubber-type projectile and stiffer than P01 and P02. Its size is exactly matches the inner diameter of the pipe and they are harder to be deformed and its surface is also smooth (see Table 2). The most interesting point here is that overall the flexible sponge balls perform much better than the rigid rubber type.

Finally, it should be pointed out that in this study, in most cases, injection causes a quicker nucleation of crystals on the surfaces than without projectiles. Two curves for 4 g/l in Fig. 3 show that at least it takes about 1.5 h before fouling resistance starts to increase without projectile injections which got quicker with injection. This can be related to the microscratches that projectiles generate on the surface which would then pave the way for faster nucleation. Nevertheless, more experimental work is needed before a solid conclusion can be drawn.

4. Conclusions

Comparative investigation of various projectiles for fouling of calcium sulphate was performed inside a heated tube. Three different types of projectiles were investigated. 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. The lack of enough exerted shear forces by these projectiles should be accounted for the lower efficiency.

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Nomenclature

A_i — inner surface area for heat transfer (m^2)
C — concentration (g/l)
C_p — specific heat capacity (J/kg K)
$\dot{m}$ — mass flow rate (kg/s)
Q — heat flow (W)
R_f — fouling resistance (m^2 K/W)
T_b — bulk temperature (K)
T_i — inner temperature (K)
T_{si} — surface temperature (K)
T_o — outer temperature (K)
U_{cl} — overall heat transfer coefficient at clean condition
U_f — overall heat transfer coefficient at fouling condition
v — velocity (m/s)

Abbreviations

3WV — three-way valve
2WV — two-way valve
EDTA — ethylenediaminetetraacetic acid

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