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Abatement of deposit formation in aqueous systems using various projectiles

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ABSTRACT

The utilization of brackish or seawater is widespread in cooling systems or in desalination plants. This would, nonetheless, lead to severe and chronic deposit formation which is extremely difficult to combat. One promising technique to mitigate fouling in tubular passages is to propel projectiles at specified injection intervals. In this study, a comparative experimental investigation of mitigating fouling is performed using seven different types of projectiles. The results showed that the flexible sponge balls were more efficient than the rigid rubber balls. Larger and harder sponge balls were more effective than smaller and softer ones as long as they can be propelled into tubes. Hard balls with exact diameter as inner diameter of the tube even worsened fouling as they may have compacted precursors on the inner wall causing even a harder and more tenacious deposit. Finally, the experimental results showed injection decreased the induction time of fouling.

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

1. Introduction

The demand for fresh water and resultant fouling/scaling are the driving forces for more efficient technologies to convert saline into potable water or to use it in cooling systems as coolant. In thermal desalination plants or cooling water systems, chemical anti-fouling agents are widely used to combat deposit formation. Nevertheless, the present stringent environmental legislations limit and even phase out the use of detrimental elements in such chemicals. Alternative mitigation techniques such as the propulsion of cleaning projectiles are also available that can be solely applied to devices with tubular conduits. The method includes slightly oversized balls or other shapes made from sponge or rubber which would pass through the heat exchangers tubes [1]. As the projectiles move, the deposit would be dislodged depending on the exerted shear and contact area between the inner surface and the projectile [2]. The projectiles circulate by a separate loop through the heat exchanger or cooling system. Due to the fluid pressure loss across the tubes, the balls are pushed through and can be re-injected after collection.

The utilization of projectiles for cleaning purposes came into force from the need to clean heat exchangers without disrupting operation. Many mechanical

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cleaning systems do not permit the cleaning of equipment without interrupting the process or manipulating the flow [1]. Moreover, the projectiles are used for situations where there is demand for maintaining a high degree of cleanliness. The advantages of this method also include the effectiveness in providing reasonably stable operating conditions. The projectiles can also be used in hygiene processes i.e. food production, where the use of cleaning chemicals are not allowed. The technology is also environmentally friendly by saving energy which otherwise would have been needed to off-set the impact of fouling. Accordingly a longer lifetime of the thermal equipment is expected. Other advantages include lower corrosion of heat transfer surfaces and avoidance of unscheduled shutdowns.

Despite significant technological advancements in using cleaning projectiles, there are still several outstanding technical limitations that should be considered i.e. (i) their thermal sustainability at high temperatures above 120°C [1]; (ii) chemical stability, (iii) mal-distribution in the header of the heat exchangers and also (iv) the requirement of relatively high velocities for the propulsion of the projectiles.

The main characteristics of projectiles include shape, size, stiffness, surface texture and density [3]. There are many types of projectiles in the market and any selection requires many considerations. The present study aims at comparing the cleaning ability of various projectiles with different hardness and sizes. A rigorous set of fouling experiments has been performed to examine their cleaning performance. The $CaSO_4$ solution was used as foulant, and different injection rates were attempted. The fouling runs were performed at accelerated conditions due to laboratory restrictions and also to rigorously characterize the impact of the projectile cleaning.

2. Experimental setup and procedure

Jalalirad et al. [1] have fully described the attempted test facility and experimental procedure thus only a brief description will be discussed here for the sake of brevity. A test rig was designed and constructed to investigate the on-line cleaning action of projectiles in tubular conduits during a fouling process. The test rig is designed such that projectiles can be shot at different injection rates and velocities during fouling runs. A schematic of the test rig is shown in Fig. 1, and a picture of the setup is shown in Fig. 2. The test rig consists mainly of a supply tank, a 3 hp centrifugal pump, heating zone, an injection system to propel projectiles inside the tube, and a transparent part made from glass pipes to ensure the return of projectiles to the injection point (see part 4 in Fig. 2). The supply tank has a volume of 60 l and it is equipped with a cooling coil and 3 jacket heaters, each of a power of 500 W to adjust the bulk temperature of the working fluid which is 40°C. The $CaSO_4$ solution is prepared separately then added to the supply tank. The $CaSO_4$ solution is pumped from the supply tank to the heating zone, i.e. the heat exchanger, via the centrifugal pump and then back to the supply tank, as indicated by the dark blue lines in Fig. 1. An in-line 70- μm filter is also used to remove suspended particles or broken deposits in the flow. The filter is installed after the pump and before the heat exchange section, as shown in Fig. 1. It is made from polyethylene and polypropylene and it is 0.5 m long. The flow rate is controlled by a flow-meter and a three-way valve (3WV) that is fully actuated by a motor, as shown in Fig. 1. The flow rate is measured by the flow-meter and compared to the set flow, based on that the 3WV is actuated automatically, and the excessive flow is returned back to the tank through a bypass line. The rig is also equipped with two pressure transducers before and after the heating zone. Nevertheless several attempts failed to draw meaningful pressure readings due to large fluctuations especially when the projectile was injected.

The heating zone consists of a circular tube heated from outside by an electrical heater with a maximum power of 10 kW. Heat is transferred from the electrical heater to the $CaSO_4$ solution passing through the heated tube which is made from stainless steel 316 and has an inner diameter of 20 mm, thickness of 2.0 mm and length of 280 mm, respectively. Two K-type thermocouples with diameter of 0.5 mm have been mounted in the wall of the heated tube, in order to measure the surface temperature which in turn facilitates the determination of fouling resistance. The Wilson-plot [4] is used to determine the surface temperature of the pipe. The temperature and pressure of the $CaSO_4$ solution before and after the heating zone are measured via thermocouples and pressure transducers.

The projectile injection system is highlighted in Fig. 1 by the dotted circle. The projectile is first inserted in the test rig via an inclined tube shown in upper left corner of Fig. 1. It is then shot into the heated tube by turning the flow through the 3WV, such that the flow passes from outlet (2) of the 3WV to the heat exchanger tube. The projectile is recirculated to a transparent section to confirm that it is not stuck anywhere in the test rig. The projectile is returned back to its initial position by opening the two-way valves, such that a small flow brings the projectile to its first position for the next injection. The

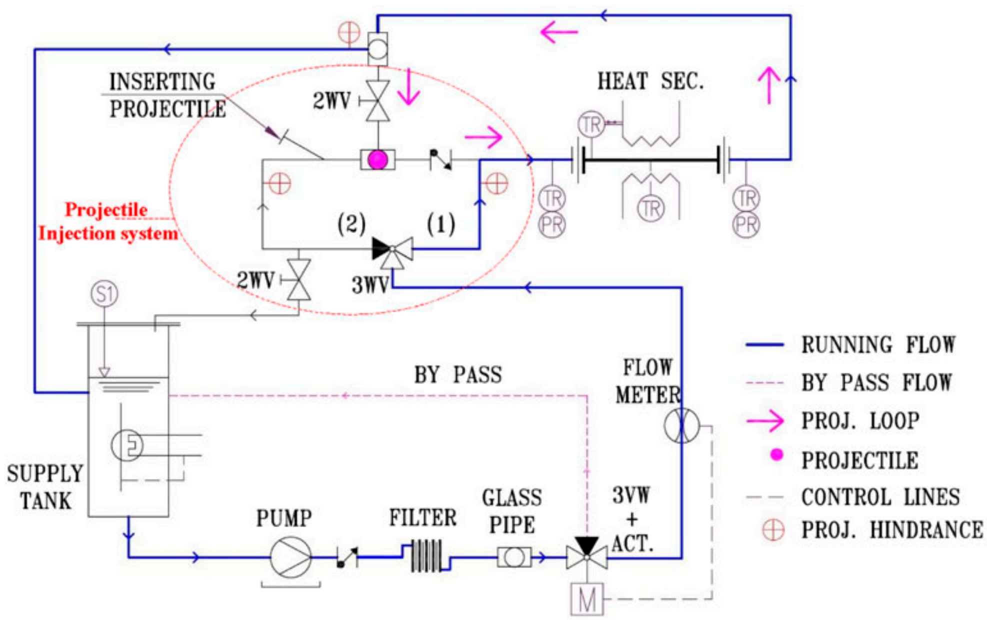

Fig. 1. Flow diagram of the fouling test facility.

Fig. 2. A photo of the experimental setup, (1) 3 hp centrifugal pump, (2) 60 l supply tank, (3) a 3 WV that is fully actuated by a motor and a flow controller, (4) a 10 kW electrical furnace, (5) 70 μm filter, (6) piping and (7) control panel of the furnace.

Table 1
Range of operating conditions

Parameters	Range
Bulk temperature	40℃
Velocity	0.5–3.0 m/s
Chemical concentration	3.0–5.0 g/l
Surface temperature in heated tube	71–80℃
Inside diameter of heated tube	20.0 mm
Length of heat section	28 cm
Min. projectile interval	20 s
Max. Power of furnace	10.5 kW
Maximum heat flux	570 kW/m^2
Maximum temperature of furnace	1,600℃

range of operating conditions that can be achieved by the test facility is given in Table 1.

3. Specifications of projectiles

Seven types of projectiles were used as specified in Table 2. The projectiles were of spherical shape but differed in size and hardness. The harder and larger the projectiles were, the more efficient cleaning was expected as then they needed to produce enough shears to remove deposit after nucleation. Accordingly, the diameter of the most projectiles has been selected to be larger than the diameter of the heated tube to produce enough shear to remove deposits or to dislodge nucleated crystals. Projectile P01 is 5% bigger than inner diameter of pipe and soft just enough to wipe out any initial nucleated crystals. P02 is 10% bigger and harder to produce more shears to remove deposit when the fouling rate was relatively high. P04, P11, P12 and EX06 are characterized as hard projectiles yet with different sizes.

The shear stresses listed in the table are also the ones that would be exerted by the attempted projectiles on the surface. They were measured by using a force measurement device when the projectiles were pulled in the tube under constant velocity. As

Table 2
Specification of attempted projectiles

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		
τ_{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 Smooth surface	Rubber-ball Smooth surface	Rubber-ball Smooth surface	Rubber-ball Smooth surface
Stiffness (N/% def.)	1.040	1.040	1.040	1.040
τ_{dyn}(kPa)	loose	loose	negligible	932

expected larger and harder projectiles would require more forces to be propelled inside the tube but would produce larger shears. It should be pointed out that there is no limit of using larger projectiles as long as operating conditions allow i.e. pressure drop across the exchanger.

4. Preparation of $CaSO_4$ solution

Calcium sulphate, which is used as foulant in this investigation, has an inverse solubility with temperature above 40˚C [5]. This solubility is strongly a function of the presence of other ions [6] in water, thus demineralized water with a conductivity of 50 μS/cm is used. Since calcium sulphate crystals do not dissolve easily in water, calcium nitrate tetrahydrate ($Ca(NO_3)_2.4H_2O$) and sodium sulphate (Na_2SO_4) are dissolved together in water to produce a calcium sulphate dihydrate solution. These two chemicals are chosen because their high solubility in water could provide an ample concentration of foulant ions in the solution, as have been shown by Najibi [7]. Besides, the resulting sodium nitrate ($NaNO_3$) improves the solubility of calcium sulphate, and the reasoning behind that has been explained by Marshall et al. [6] and Rizzo et al. [8]. They attributed this to the electrostatic attraction between the sodium nitrate ions and the ions with opposite charge formed by the calcium sulphate.

Several experiments were performed to determine the suitable bulk concentration. It was observed that in order to produce fouling at measurable rates, the calcium sulphate solution had to be supersaturated with a bulk concentration above 4 g/l. The prepared test solution is saturated calcium sulphate solution of bulk concentration 4.6 g/l. Several tests have been performed to exclusively investigate the possibility of bulk crystallization. In the experiments where the fouling layer had reached to an asymptotic level, the experiments were kept running afterwards for several hours and the bulk concentration was continuously monitored. It was found that the bulk concentration did not change, therefore, it can be concluded that bulk crystallization did not take place. Hence the possibility of crystallization in bulk liquid was ruled out in all fouling experiments considering that heterogeneous nucleation, i.e. on the heat transfer surface, requires less energy than homogeneous nucleation in liquid [9]. Half of the volume of the supply tank, i.e. 30 l, is filled with demineralized water at the beginning of each experiment, and then we start running the setup by turning on the pump and the electric heater. Two 15 litres of calcium nitrate tetrahydrate and sodium sulphate solutions are heated to 40°C in separate thermostat tanks, and then added to the supply tank once the temperature of the electrical heater as well as the bulk temperature of the circulating water have reached a steady state condition. The two solutions are mixed immediately due to high turbulence in the supply tank forming $CaSO_4$ based on the following chemical reaction:

$$Ca(NO_3)_2.4H_2O + Na_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O + 2NaNO_3 + 2H_2O$$

The concentration of $CaSO_4$ during the fouling experiments was determined by a complexometric Ethylene-Diamine-Tetra-Acetic (EDTA) acid titration and then controlled by the addition of respective solutions. The titration is done every half an hour. The concentration of the $CaSO_4$ decreases during the initial period of fouling process due to rapid formation of deposit, thus to maintain its set value a highly concentrated solution of calcium nitrate and sodium sulphate have to be added. Furthermore, the chemical adjustment may lead to increase in the presence of other ions such as NO_3 and Na in the solution which would cause the solubility of calcium sulphate to increase [10]. However rigorous previous tests in the same test rig, found the effect of such ions on fouling behaviour is negligible [11].

5. Experimental procedure and data reduction

Consistency of the experimental procedure is of prime importance due to the dominant influence of initial conditions on the subsequent deposition of precursors. At the beginning of each fouling run, various components of the test rig i.e. supply tank, filter, heating zone have to be checked to see if there is any deposit left from the previous experiment. A fouling experiment is started by turning on the pump and the electric heater. The heater temperature is set to increase at a rate of 10°C per minute. This is in order to maximize the lifetime of the heater. 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 the flow-meter and the three-way valve plus actuator. The data acquisition system is switched on to assess the stability of operating conditions. The bulk temperatures and the heater reach steady state conditions after approximately 2 h of heating. Once steady-state conditions are confirmed, then the fouling process is started by adding in the calcium nitrate tetrahydrate and sodium sulphate solutions in the supply tank. The data acquisition system is then set to record all inputs every one minute and stores it as a Microsoft Excel spread-sheet. The fouling process is characterized by the thermal resistance R_f of the fouling layer, which is calculated from the overall heat transfer coefficients at clean and fouling conditions as:

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

where U_f and U_c are the overall heat transfer coefficients at fouling and clean conditions, respectively. The overall heat transfer coefficient U is calculated from the following equation,

$$U = \frac{Q}{A_i \times (T_s - T_b)} \tag{2}$$

where T_s is the temperature of the inner surface of the heated tube. The inner surface temperature T_s is calculated based on the Wilson-plot [4] and using the two inserted thermocouples in the middle of the heated tube. T_b is the flow bulk temperature, A_i is the inner surface area of the heated tube, and Q is the rate of heat transfer across the heated tube which can be calculated from,

$$Q = \dot{m} \times c_p \times (T_o - T_i) \tag{3}$$

$\dot{m}$ is the mass flow rate, c_P is the specific heat capacity of the flow and T_o and T_i are the outlet and inlet temperatures of the flow from and to the heated tube, respectively. The bulk temperature T_b is obtained by averaging the two bulk thermocouple readings, T_o and T_i. Q is the heat flux and it is equal to

$$q = \frac{Q}{A_i} \tag{4}$$

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 in order to see the fouling layer in the heat section. The pictures 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 cleaning chemical agents are inert such that it does not react with the surface of the tubes. Due to the sensitivity of the performed experiments, the reproducibility of these experiments has been checked by repeating the experiments. It has been found from the performed tests that the reproducibility of the performed experiments varies between 85 and 90%.

6. Experimental uncertainty and error analysis

Experimental errors consist of bias and precision errors, which determine the uncertainty in the measured quantity. The knowledge of the uncertainty in a single experiment is important as it helps in evaluating the results. The uncertainty C is related to the bias error B and the precision error P for a 95% confidence by,

$$C = \sqrt{(B^2 + P^2)} \tag{5}$$

The thermal resistance R and the resulting bias error B_R are calculated from,

$$R = \frac{T_s - T_b}{q} = \frac{\Delta T}{q} \tag{6}$$

and

$$\left(\frac{B_R}{R}\right)^2 = \left(\frac{B_q}{q}\right)^2 + \left(\frac{B_{T_s}}{\Delta T}\right)^2 + \left(\frac{B_{T_b}}{\Delta T}\right)^2 \tag{7}$$

respectively. B_q, $B_{T_s}$and $B_{T_b}$are the bias error of the heat flux q, surface temperature T_s and the bulk temperature T_b, respectively. The precision error P_R of the measured thermal resistance R is calculated from the standard deviation of a set of n observations as follows,

$$P_R = \sqrt{\left(\frac{\sum_{i=1}^{n} (R - \bar{R})^2}{n(n-1)}\right)} \tag{8}$$

where $\bar{R}$ is the average thermal resistance of the n observations. The precision error is calculated based on 20 readings, i.e. $n = 20$. Based on Eq. (5–8), it is found that the uncertainty in the measured thermal resistance of the performed experiments does not exceed 4%.

7. Results and discussion

7.1. Fouling curve for different velocities without projectiles

Fouling experiments were initially performed without injecting projectiles at different velocities to assess the performance of projectiles under similar operating conditions. Fig. 3 shows the fouling curve for two velocities of 0.8 and 2.2 m/s where the first represents the minimum velocity for the propulsion of projectiles and the latter was the recommended value followed in industry. The surface temperature and concentration were 80˚C and 3.8 g/l, respectively. As it can be seen for a higher velocity of 2.2 m/s, the rate of fouling is slower confirming that the velocity has a suppressing impact of deposit formation. A jump after 5 h of operation for lower velocity implies incidental formation of crystals on the spot where thermocouples were embedded. Similarly, a reduction for a velocity of 2.2 m/s indicates that a part of deposit would have been removed during the run even without injecting any projectile. Sudden and sharp drops of fouling resistance can be explained by the flow shear that can remove fragile parts of the fouling layer. Contrariwise, increase in fouling resistance is more difficult to explain, but reattachment of larger particles on the surface which were re-circulating in the rig can be accounted for.

7.2. Effect of projectile type

Fig. 4 presents fouling resistances for the same operating conditions for four different projectiles. Bulk temperature was 40˚C and the velocity, surface temperature and concentration were 0.8 m/s, 80˚C, 3.8 g/l, respectively, for an injection interval of 1 inj/5 min. While P01 and P02 were sponge type with the

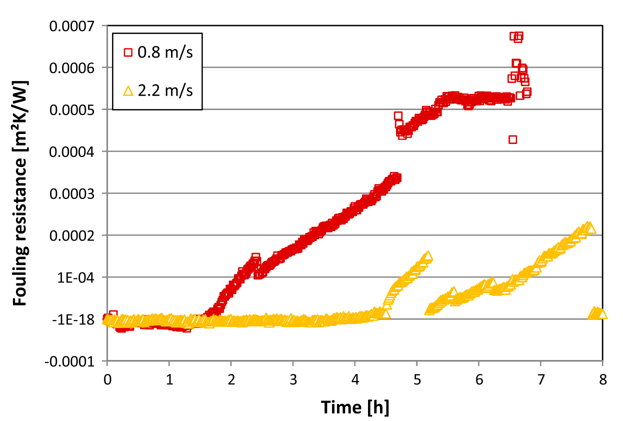

Fig. 3. Fouling resistance vs. time for different velocities without injecting projectiles. (Bulk and surface temperature of 40 and 80˚C and concentration of 3.8 g/l).

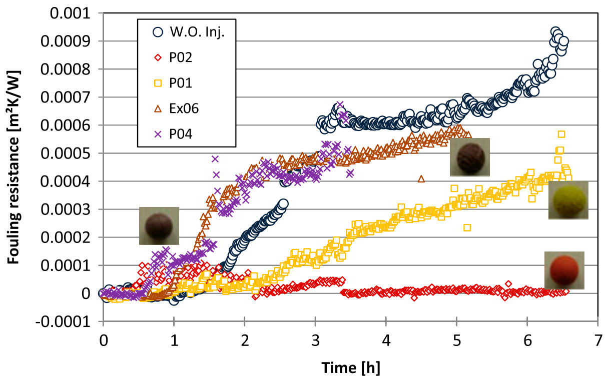

Fig. 4. Comparison of various projectiles on cleaning for the same injection intervals of 5 min. (Bulk temperature 40°C, velocity 0.8 m/s, surface temperature 80°C, concentration 3.8 g/l).

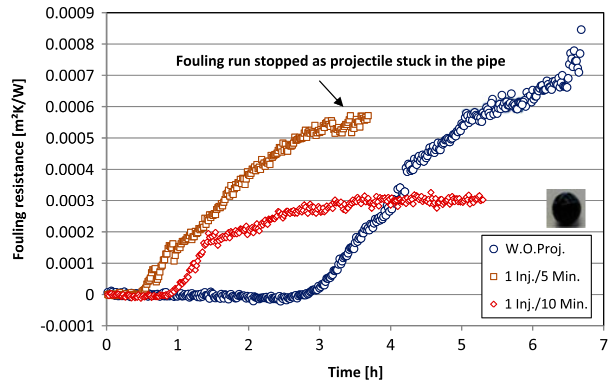

Fig. 6. Impact of P11 on fouling resistance at different injection frequencies. (Bulk temperature 40°C, velocity 1.3 m/s, surface temperature 71°C and concentration 4.6 g/l).

diameter bigger than the pipe, they could partly be squeezed hence passed easily through the pipe. P02 is harder and bigger than P01, see Table 2. The results show that P02 shows better efficiency in keeping the surface clean. EX06 and P04 are rubber types and stiffer than P01 and P02 but their sizes matched the inner diameter of pipe just with a clearance of 0.1 mm. As it can be seen that they did not have any meaningful impact only cleaning the surface let alone that they have even worsened cleaning up to 3.5 h when compared with no injection. Overall, the flexible sponge balls perform much better than the rigid-rubber types.

7.3. Effect of loose projectiles

Figs. 5 and 6 show the performance of P04 and P11 at higher injection intervals. The bulk temperature was 40°C and velocity, surface temperature and concentration were 1.3 m/s, 71°C and 4.6 g/l, respectively. Injection intervals were in 5 and 10 min. Not only they did not clean the pipe, instead they even accelerated the deposit formation. It was also observed in 10 min injection, projectiles were stuck when encountered the deposit in the pipe. Sticking is also a main problem in working with projectiles and should be investigated further.

7.4. Performance of hard projectiles

Unlike loose projectiles, Fig. 7 indicates that for hard projectiles the injection interval also has some consequences on cleaning. Operating conditions are the same as previous run reported for the loose projectiles. Injections were done every 5, 10 and 15 min and also without injection. For example injection in 5 min implies to some extent a good cleaning performance but in 10 and 15 min the results are totally different

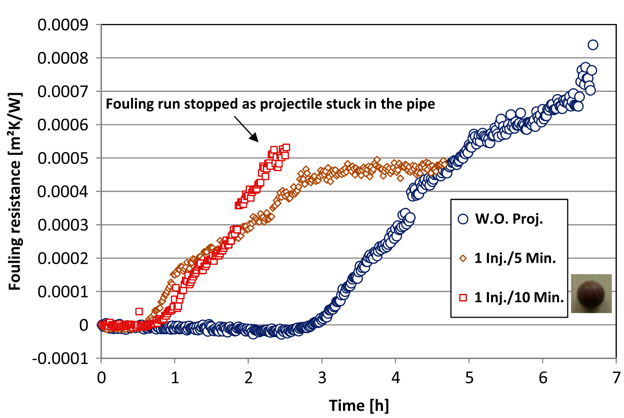

Fig. 5. Impact of P04 on fouling resistance for different injection intervals. (Bulk temperature 40°C, velocity 1.3 m/s, surface temperature 71°C and concentration 4.6 g/l).

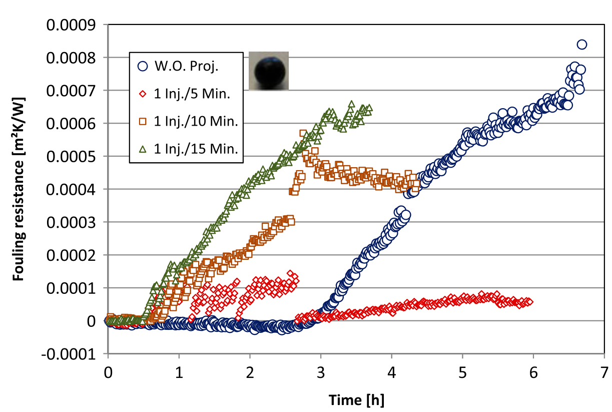

Fig. 7. Effect of P12 on cleaning for different injection frequencies. (Bulk temperature 40°C, velocity 1.3 m/s, surface temperature 71°C and concentration 4.6 g/l).

and they even worsened the deposit formation. It means long intervals like 10 or 15 min is not enough for cleaning but the presence of air bubbles because of injection and maybe the deposit residues left on the surface from previous injection intensifies nucleation and so does the deposit formation.

5. Conclusions

Projectiles decrease the induction period, fouling rate and asymptotic fouling resistance. The asymptotic fouling can be approached much quicker compared to those of no injection. Soft sponge balls are more efficient than rigid rubber balls. Between soft projectiles, larger and stiffener sponge balls are more effective than smaller and softer types only if they can be propelled inside the tube. Rigid and hard balls with exact diameter of the pipe have even worsened the deposition process due to instability in contact and also as they may compact the deposit on the inner wall of the tube.

The lack of enough exerted shear forces by sponge type projectiles should be accounted for the lower efficiency. For both types of projectiles (sponge and rigid) also the initial deposition of crystals was faster due to the scratch of the surface in micro-scale and presence of air bubbles when injecting the projectiles.

Abbreviations

EDTA	—	Ethylene-diamine-tetra-acetic
inj	—	injection
Proj	—	projectile
2WV	—	two-way valve
3WV	—	three-way valve
$CaSO_4$	—	calcium sulphate anhydrite
$Ca(NO_3)_2{\cdot}4H_2O$	—	calcium nitrate Tetrahydrate
Na_2SO_4	—	sodium sulphate
$NaNO_3$	—	sodium nitrate

Greek symbols

τ_{dyn}	—	dynamic wall shear stress (Pa)

Notations

A_i	—	inner surface area of the heated tube
B	—	bias error
C	—	uncertainty or constant in Eq. (5)
c_p	—	specific heat capacity (J/kg·K)
m	—	deposit mass (kg)
P	—	precision error
Q	—	rate of heat transfer (W)
q	—	heat flux (W/m^2)
R_f	—	fouling resistance ($m^2{\cdot}K/W$)
T_b	—	bulk temperature of the flow (°C)
T_i	—	flow inlet temperature to the heat exchanger (°C)
T_o	—	flow outlet temperature from the heat exchanger (°C)
T_s	—	temperature of the inner surface of the heated tube (°C)
t	—	time
U	—	overall heat transfer coefficient ($W/m^2{\cdot}K$)
v	—	velocity (m/s)

Subscripts

b	—	bulk
c	—	clean
f	—	fouling
i	—	inlet
o	—	outlet
s	—	surface

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