

## OPTIMUM INJECTION PERIOD OF SPHERICAL PROJECTILES IN TUBULAR HEAT EXCHANGERS

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### ABSTRACT

The objective of this study was to determine the optimum period of injection for propulsion of a spherical projectile in a single heated plain tube which would represent tubular heat exchangers. An experimental set-up has been designed and constructed to study fouling with or without using projectiles to mitigate deposition. Fouling experiments have been performed in which  $\text{CaSO}_4$  was used as foulant. It has been found that the injected projectile reduces the induction time compared to those experiments without projectiles. The cleaning action of projectiles is relatively profound at the beginning of the fouling process and decreases as the fouling layer builds up till it diminishes to zero when the asymptotic behaviour is approached. Therefore, it is better to inject the projectiles after the induction period to make use of the long fouling free period of operation in case of no injection, and to stop injection as the asymptotic behaviour is approached, since the projectiles become ineffective at the asymptotic stage.

### INTRODUCTION

Crystalline deposits on heat transfer surfaces, which is known as crystallization fouling, reduce the efficiency of heat exchangers considerably due to their low conductivity. Crystalline deposits on heated surfaces are formed from salts whose solubility decreases with increasing temperature, (Bott, 1988). In particular, in desalination plants (Zhao and Chen, 2011; Austin et al., 1975), crystallization fouling can lead to inefficient operation and sometimes operation failure, causing even unscheduled shut-down for maintenance. Many mitigation techniques have been developed to minimize and if possible to prevent crystallization fouling. Müller-Steinhagen et al. (2011) have summarized the main methodologies for mitigation of fouling in industrial heat exchangers. They concluded that fouling can effectively be mitigated firstly by proper design of heat exchangers and secondly by on-line cleaning techniques. As for the latter, one practical technique is the injection of projectiles (Hamed et al., 2007; Al-Bakeri and El Hares, 1993), e.g. sponge balls, through the heat exchanger tubes to remove deposits. Jalalirad et al. (2012) performed a comprehensive set of crystallization fouling

experiments with and without projectiles, and found that the capability of cleaning by the projectile is substantial at the beginning of the fouling process but decreases as the fouling layer develops. They concluded that the structure, hardness, and morphology of the deposit layer are of prime importance.

Esawy et al. (2010) and Malayeri et al. (2005) studied  $\text{CaSO}_4$  deposition on heat transfer surfaces during pool boiling and found that the fouling layer structure was crystalline at the beginning of the fouling process, but hard and more compact at the asymptotic stage of the fouling process. It can thus be concluded that the change in the deposit layer structure can probably affect the cleaning action of projectiles during the fouling process. The objective of this research is to determine experimentally the optimum period of injection in order to minimize the energy used for injection and to maximize the cleaning action of projectiles. Fouling experiments have been performed in which  $\text{CaSO}_4$  is used as foulant under different operating conditions and the fouling resistance is measured continuously during the whole experiment. The projectiles were introduced in a single plain and circular tube which is heated from outside via an electrical heater. Spherical projectiles are injected through the heat exchanger tube via an injection system. Projectiles at an injection rate of 1 inj./10 min have been investigated to discern their influence on the fouling process.

### EXPERIMENTAL SETUP AND EXPERIMENTAL PROCEDURE

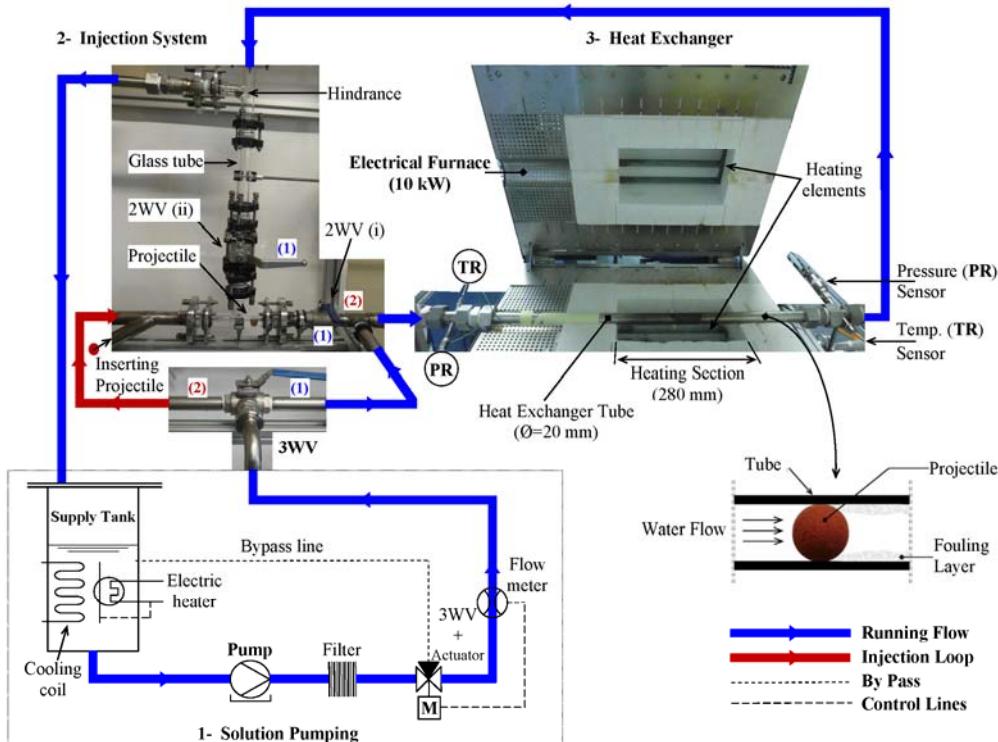
#### Experimental Setup

A test rig was designed and constructed to investigate the on-line cleaning action of projectiles in tubular heat exchangers during a fouling process. The test rig is designed such that projectiles can be injected at different injection rates and at different velocities during a fouling process. A schematic of the test rig is shown in Fig. 1, and an image of the setup is shown in Fig. 2. The test rig consists of 3 main sections, (1) a solution pumping system, (2) a projectile injection system made from transparent glass pipes to ensure the return of projectiles to the injection

point and (3) the tubular heat exchanger under investigation, as indicated in [Fig. 1](#). The pumping system consists of a solution supply tank, a centrifugal pump to circulate the flow, a water filter to remove suspended particles and a 3 WV to control the flow. 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 flowing solution to a desired value, which is 40°C in this study. The CaSO<sub>4</sub> solution is prepared separately then added to the supply tank. The CaSO<sub>4</sub> solution is pumped from the supply tank to the heating section, 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 used to remove suspended particles 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 heat exchanger is a circular tube heated from outside via an electrical heater of a maximum heating power of 10 kW. Heat is transferred from the electrical heater to the CaSO<sub>4</sub> solution passing through the heat exchanger tube. The heat exchanger tube has an inner diameter of 20 mm, thickness 2.5 mm, length 280 mm, and it is made from Stainless Steel 316. Two K-type thermocouples with diameter of 0.5 mm have been mounted in the wall of the

heat exchanger tube, in order to measure the surface temperature which in turn facilitates the determination of fouling resistance. The Wilson test (Briggs and Young, 1969) is used to determine the surface temperature of the pipe. The temperature and pressure of the CaSO<sub>4</sub> solution before and after the heating zone are measured via thermocouples and pressure transducers. A projectile is inserted in the test rig via the inserting projectile tube, i.e. the inclined tube shown in upper left corner of [Fig. 1](#). The projectile is injected into the heat exchanger 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 projectile used is a *spherical rubber ball* that has a diameter of 20.2 mm, which is 1 % larger than the inner diameter of the tube of the heat exchanger. The projectile is hard with a stiffness of 0.558 N/% deformation (Jalalirad and Malayeri, 2013). The diameter of the projectile has been selected to be larger than the diameter of the HE tube to produce enough shear stresses to remove deposits and to wipe out nucleated crystals. It should be pointed out that air bubbles are created during the injection of projectiles and it is inevitable because of i) desorbed air in the water, ii) the turbulence in the flow that is caused by the projectile and iii) the open cycle of operation that sucks air into the flow. The range of operating conditions that can be achieved by the built up setup are given in [Table 1](#).



**Fig. 1.** A schematic of the experimental setup equipped with the projectile injection system.



**Fig. 2.** A photo of the experimental setup; (1) 3 hp centrifugal pump, (2) 60 l water tank, (3) a 3 kW that is fully actuated by a motor and a flow controller, (4) a 10 kW electrical furnace, (5) 70  $\mu\text{m}$  filter, (6) piping (7) control panel for the furnace.

**Table 1.** Range of operating conditions that can be achieved by the experimental setup.

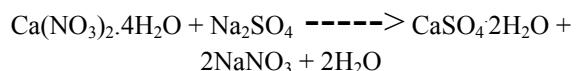
Variable	Range
Bulk temperature, $T_b$	40 – 80°C
Flow velocity	0.5 to 3.5 m/s
Chemicals	$\text{CaSO}_4$
Concentration	4.6 g/l
Maximum surface temperature in tube, $T_s$	135 °C
Inside diameter of tube	20.0 mm
Minimum injection rate	1 inj./min.
Maximum heat flux, $q$	570 $\text{kW}/\text{m}^2$

### Preparation of $\text{CaSO}_4$ Solution

Calcium sulphate is used as a foulant which has an inverse solubility with temperature above 40°C (Bott, 1988). This solubility is strongly a function of the presence of other ions (Marshall, 1964) in the water, thus demineralised water with a conductivity of 50  $\mu\text{S}/\text{cm}$  is used. Since calcium sulphate crystals do not dissolve easily in water, therefore, it was preferred to dissolve calcium nitrate tetrahydrate ( $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ) and sodium sulphate ( $\text{Na}_2\text{SO}_4$ ) together in water to produce a calcium sulphate dihydrate solution. These two chemicals are chosen because their high solubility in water could provide a high enough concentration of foulant ions in the solution, as have been shown by Najibi (1997). Besides, the resulting sodium nitrate ( $\text{NaNO}_3$ ) improves the solubility of calcium sulphate, and the reasoning behind that has been explained by Marshall et al. (1964) and Rizzo (2008) as due 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 (Esawy et al., 2010), i.e. no more developing of the fouling layer, the experiments were kept running afterwards for several hours and the bulk concentration was checked continuously. 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 crystallisation 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 (Al-Janabi, et al., 2009a).

Half of the volume of the supply tank, i.e. 30 l, is filled with demineralised 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 liters 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  $\text{CaSO}_4$  based on the following chemical reaction (Fritz and Schenk, 1987; Al-Janabi et al., 2009b).



The concentration of  $\text{CaSO}_4$  during the fouling experiments was determined by a complexometric Ethylene-Diamine-Tetra-Acetic (EDTA) acid titration (Fritz and Schenk, 1987) and then controlled by the addition of respective solutions. The titration is done every half an hour, and details about the titration method could be found in (Esawy, 2011). The concentration of the  $\text{CaSO}_4$  decreases during the fouling process, and to maintain its set value a highly concentrated solution of calcium nitrate and sodium sulphate are added to the supply tank to maintain the desired bulk concentration. It should also be pointed out that a scanning electron microscope analysis of the formed deposits resulting from the above chemical reaction confirmed that the deposits are in form of calcium sulphate dihydrate ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ).

### 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 experiment, various components of the test rig i.e. supply tank, filter, heating zone have to be checked to see if there any deposit is 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 3-Way-Valve plus actuator. The data acquisition system is switched on to assess the stability of operating conditions. Temperatures of bulk and the electrical heater reach steady state condition 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 minute and stores it as a Microsoft Excel spreadsheet. 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 follows,

$$R_f = \frac{1}{U_f} - \frac{1}{U_{cl}} \quad (1)$$

where  $U_f$  and  $U_{cl}$  are the overall heat transfer coefficients under fouling and clean conditions, respectively. The overall heat transfer coefficient  $U$  is calculated from the following equation,

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

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 (Briggs and Young, 1969) 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 heat exchange tube and it can be calculated from,

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

$\dot{m}$  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 heat exchanger, respectively. The bulk temperature  $T_b$  is obtained by averaging the two bulk thermocouple readings,  $T_o$  and  $T_i$ .

### Experimental Uncertainty and Error Analysis

Experimental error consists 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  $B$  (systematic) and the precision error  $P$  (random) for a 95 % confidence by (Al-Janabi et al., 2009c; Figliola and Beasley, 1991),

$$C = \sqrt{[B^2 + P^2]} \quad (4)$$

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

$$R = \frac{T_s - T_b}{q} = \frac{\Delta T}{q} \quad (5)$$

and

$$\left( \frac{B_R}{R} \right)^2 = \left( \frac{B_q}{q} \right)^2 + \left( \frac{B_{T_s}}{\Delta T} \right)^2 + \left( \frac{B_{T_b}}{\Delta T} \right)^2, \quad (6)$$

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.  $q$  is equal to the rate of heat transfer  $Q$  per unit area  $A_i$ . 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,

$$P_R = \sqrt{\frac{\sum_{i=1}^n (R - \bar{R})^2}{n(n-1)}} \quad (7)$$

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 equations (7), it is found that the uncertainty in the measured thermal resistance of the performed experiments does not exceed 2%.

### EXPERIMENTAL RESULTS AND DISCUSSION

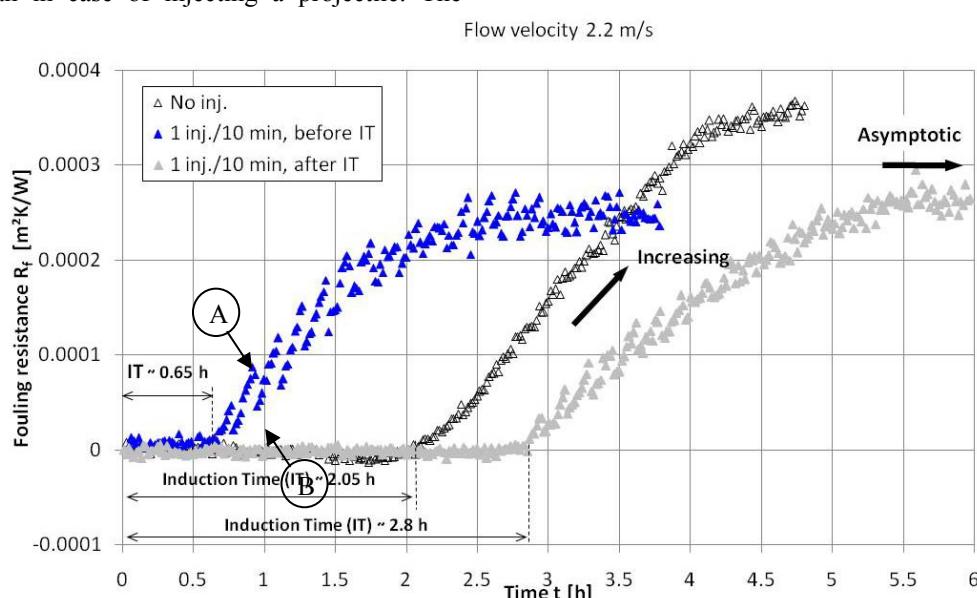
Several experiments have been performed to investigate the influence of the injected projectile on the fouling process. The development of fouling resistance  $R_f$  in case of with/without a projectile is shown in Fig. 3. The development of the fouling resistance in case of i) no injection, ii) injecting the projectile from the beginning of the induction period and iii) injecting a projectile at the end of the induction period are shown in Fig. 3. The flow velocity is 2.2 m/s, the injection rate is one projectile every 10 minutes and the  $\text{CaSO}_4$  concentration has been adjusted to 4.6 g/l. The induction time in case of no injection of a projectile is 2.05 h, but with a projectile injection from the beginning of operation is 0.65 h, which is reduced by approximately threefold. The influence of projectiles on the induction time has been studied and explained by Abd-Elhady et al. (2014). The fouling resistance in case of no injection is continuous in the attempted duration. Nonetheless, in case of projectile injection, it is intermittent and fluctuating due to the removal of same parts of the fouling layer by the injected projectile. The fouling resistance decreases as soon as a projectile is injected and then increases with time, i.e. the fouling layer builds up. The discontinuity and the size of fluctuation in the fouling resistance are quite noticeable at the early stage of fouling and decrease with time till it diminishes when an asymptote is reached. Furthermore, the intermittence in the fouling resistance coincides with the time of injection, and there are three intermittences every half an hour which is in agreement with the injection rate, i.e. 1 injection every 10 minutes. It can be concluded that the projectile is capable of removing parts of the fouling layer at the early stage of the

fouling process, and this capability decreases as the fouling layer builds up such that the projectile is not effective anymore when the asymptotic region is approached. This is due to the change in the fouling layer structure from a soft-crystalline structure at the beginning of the fouling process to a hard-sintered structure at the asymptotic stage (Esawy et al., 2010; Malayeri and Müller-Steinhagen, 2005) that does not allow removal of particles from its surface. Furthermore, the removal efficiency of the injected projectile is a function of the fouling layer structure.

The fouling resistance at point (A), as indicated in Fig. 3, is  $1.5 \times 10^{-4} \text{ m}^2\text{K/W}$ , and then decreased to approximately  $1 \times 10^{-4} \text{ m}^2\text{K/W}$ , i.e. point (B) after injecting the projectile. The decrease in the fouling resistance from (A) to (B) is about 33%. The fouling resistance is also equal to  $\delta/k$ , where  $\delta$  and  $k$  are the thickness and thermal conductivity of the fouling layer (FL), respectively. The change in the thermal conductivity  $k$  of the FL from (A) to (B) could be assumed negligible, i.e.  $k \sim \text{constant}$ , due to the inconsiderable changes in the FL structure in that short period of time from (A) to (B). Therefore, it can be concluded that the decrease in the FL thermal resistance from (A) to (B) by 33% is mainly due to the decrease in FL thickness by 33%, which implies how powerful the cleaning effect of the injected projectile at the early stage of the fouling process.

The final asymptotic fouling resistance has reached after 3.5 h of operation in case of using a projectile, but in case of no injection the asymptotic fouling resistance was not approached even after 5 h of operation. The final asymptotic resistance in case of injecting a projectile is  $0.00025 \text{ m}^2\text{K/W}$ . However, the fouling resistance in case of no injection has approached  $0.00038 \text{ m}^2\text{K/W}$  after 5 h of operation and was still increasing, i.e. the asymptotic behaviour is not approached yet, which indicates that the final asymptotic resistance in case of no injection will be much higher than in case of injecting a projectile. The

results confirm that using projectiles accelerates the fouling process such that we approach the asymptotic behaviour quickly but the final asymptotic resistance is much lower than in case of no injection. It can be concluded from Fig. 3 that injecting a projectile expedites the fouling process, i.e. the fouling process starts early and the asymptotic behavior is reached quickly though it is much lower compared to that of no injection. Therefore, it can be concluded from the above experiments that it is highly recommended to inject projectiles only after the induction period in order i) to make use of the long induction period in case of no injection and ii) to clean the HE surface from any crystals which deposit during the induction period, and therefore, start operating once more with a clean surface and prolong the induction period. This strategy of operation, i.e. injecting projectiles at the end of the induction period, could be taken as a new operational criterion for mitigating fouling using projectiles. Another experiment has been performed to examine this strategy of operation, such that a projectile is injected at the end of the induction period. The final asymptotic resistance in case of injecting a projectile from the beginning of operation is similar to the asymptotic resistance in case of injecting a projectile at the end of the induction period, i.e.  $0.00027 \text{ m}^2\text{K/W}$ . The induction time has been prolonged from 2.05 h in case of no injection to 2.8 h in case of injecting a projectile at the end of the induction period, and decreased to 0.65 h in case of injecting projectiles from the beginning of operation, as can be seen in Fig. 4. It can be concluded that the induction time has increased by 36 % in case of injecting projectiles at the end of the induction period and decreased by 68.3 % in case of injecting the projectile from the beginning of operation. Injecting projectiles at the end of the induction period delays the fouling process, and injecting projectiles from the beginning of operation hastens the fouling process.



**Fig. 3.** Developing of the FL layer thermal resistance in case of i) no injection, ii) injecting a projectile from the beginning of the induction time (IT) and iii) injecting a projectile at the end of the induction time. The flow velocity is 2.2 m/s and the injection rate is one projectile every 10 min.

## CONCLUSIONS

The following conclusions can be drawn from the presented experimental results:

- 1- The injected projectile is capable of removing parts of the fouling layer at the early stage of the fouling process, and this capability decreases as the fouling layer builds up such that the projectile is not effective anymore when the asymptotic region is approached.
- 2- Injecting projectiles at the end of the induction period delays the fouling process, and injecting projectiles from the beginning of operation hastens the fouling process.
- 3- The optimum injection period should start after the induction period to make use of the long fouling free period of operation in case of no injection, and to stop injection as the asymptotic behaviour is approached, since the projectiles become ineffective at the asymptotic stage.

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## NOMENCLATURE

### Symbols

$A_i$	Inner surface area of the heated tube, $\text{m}^2$
B	Bias error %
C	Uncertainty %
$c_p$	Specific heat capacity, $\text{J/kgK}$
$\delta$	Thickness of the fouling layer, $\text{m}$
k	Thermal conductivity of the fouling layer, $\text{W/mK}$
$\dot{m}$	Mass flow rate, $\text{kg/s}$
P	Precision error %
Q	Rate of heat transfer, $\text{W}$
q	Heat flux, $\text{W/m}^2$
n	Number of observations, [-]
$R_f$	Thermal resistance of the fouling layer, $\text{m}^2\text{K/W}$
$T_b$	Bulk temperature of the flow, $^\circ\text{C}$
$T_i$	Flow inlet temperature to the heat exchanger, $^\circ\text{C}$
$T_o$	Flow outlet temperature from the heat exchanger, $^\circ\text{C}$
$T_s$	Temperature of the inner surface of the heated tube, $^\circ\text{C}$
t	time, $\text{h}$
U	Overall heat transfer coefficient, $\text{W/m}^2\text{K}$

### Subscripts

b	bulk
cl	clean
f	fouling
i	inlet
o	outlet
s	surface

## Abbreviations

EDTA	Ethylene-Diamine-Tetra-Acetic
FL	Fouling Layer
HE	Heat Exchanger
IT	Induction Time
inj	Injection
Proj	Projectile
2WV	Two Way Valve
3WV	Three Way Valve
$\text{CaSO}_4$	Calcium Sulphate anhydrite
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	Calcium Nitrate Tetrahydrate
$\text{Na}_2\text{SO}_4$	Sodium Sulphate

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