

## MITIGATION OF CRYSTALLIZATION FOULING USING PROJECTILES IN A SINGLE HEATED TUBE

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### ABSTRACT

Fouling of heat exchangers is a prevalent operating drawback in many industries. Efficient chemical inhibitors have predominantly been used for many years to combat deposit formation. Nevertheless new stringent environmental legislations limit their utilization. In the present experimental study, two spherical type projectiles of different sizes and hardness have been used to clean the inner surface of a single heated tube which was subjected to the deposition of calcium sulphate. Projectiles were then injected at different time intervals of injection of every 2, 5, 10, 15, and 30 minutes. The experimental results show that i) the projectiles would expedite initial nucleation of crystals even if they are soft and easy to propel inside the tube and ii) fouling can only be mitigated if the projectiles exert a shear force that its corresponding removal rate is greater than the net rate the deposition.

### INTRODUCTION

Heat exchangers are the workhorse of most chemical, petrochemical, food processing and power generating processes. Of many types of heat exchangers, approximately 60% of the market is still dominated by the shell and tube heat exchanger. It is largely favoured due to its long performance history, relative simplicity, and its wide temperature and pressure design ranges [1]. The global heat exchanger market is estimated to top a total of \$12.7 billion in 2012 with an increase of 3-5% per annum [2]. Despite this very positive market trend, manufacturers are under increasing pressure to produce heat exchangers which are more efficient in terms of heat recovery and use of material, while at the same time being faced with fluids which are increasingly difficult to process. One major problem directly related to these requirements is the deposition of unwanted materials on the heat transfer surfaces, which occurs in the majority of heat exchangers.

Fouling may cause one or more of several major operating problems: i) loss of heat transfer, ii) under-deposit corrosion, iii) increased pressure loss and v) flow mal-distribution.

There are many different mitigation techniques available in the market to keep the surfaces of heat exchangers clean to some extent. Nevertheless, the successful application of any such technique requires in-depth understanding of respective fouling mechanisms which otherwise may even lead to counter-productive result of increased deposition.

Among different mechanical techniques, projectiles of different shapes e.g. sponge balls and wire brushes can be propelled through the heat exchanger tubes to mitigate deposition. Projectile cleaning is ideal as it can be applied at frequent intervals and will mitigate fouling on a continuous basis. Thus the degradation of heat exchanger efficiency can be controlled. The frequency and duration of application depends on the severity of fouling and the strength of interaction between cleaning projectile and deposit. Nonetheless the experimental data about the performance of various projectiles is scarce and non-conclusive [3-4].

The present study as part of a European project "Clean-Ex" aims at investigating the performance of various projectiles under harsh fouling environments. Due to laboratory restriction, the fouling runs were conducted at accelerated conditions to rigorously characterize the impact of projectile cleaning in terms of injection time intervals and various types of projectiles in relatively short period of time.

### NOMENCLATURE

$A_i$	[m <sup>2</sup> ]	Inner surface area for heat transfer
$C$	[-]	Constant in equation (1)
$C_b$	[kg/m <sup>3</sup> ]	Concentration
$C_p$	[J/kg.K]	Specific heat capacity
$m$	[kg]	Mass of fouling
$m_f$	[kg/m <sup>2</sup> ]	Mass of deposition per unit area
$\dot{m}$	[kg/s]	Mass flow rate

$\dot{m}_d$	[kg/m <sup>2</sup> ·s]	Deposition rate
$m_r$	[kg/m <sup>2</sup> ]	Mass removed per unit area
$\dot{m}_r$	[kg/m <sup>2</sup> ·s]	Removal rate
Q	[W]	Heat flow
$R_f$	[m <sup>2</sup> ·K/W]	Fouling resistance
t	[s]	Time
$T_b$	[K]	Bulk temperature, K
$T_i$	[K]	Inlet temperature, K
$T_s$	[K]	Surface temperature, K
$T_o$	[K]	Outlet temperature, K
$U_c$	[W/m <sup>2</sup> ·K]	Overall heat transfer coefficient at clean condition
$U_f$	[W/m <sup>2</sup> ·K]	Overall heat transfer coefficient at fouling condition
v	[m/s]	Fluid velocity

### Greek Symbols

$\psi$	[-]	Strength of deposit to surface
$\lambda_f$	[W/m·K]	Thermal conductivity of fouling layer
$\rho_f$	[kg/m <sup>3</sup> ]	Density of fouling layer
$\tau$	[Pa]	Wall shear stress

### EXPERIMENTAL SET-UP

A test rig was designed and constructed to simulate conditions under which crystallization fouling would occur. The rig includes an online cleaning device which enables introduction of projectiles for various operating scenarios e.g. i) continuous basis or ii) injection of projectiles in different time intervals. The projectiles pass through a single tube where the part is middle is heated up for investigating fouling on the inner surface of the tube. A simple flow chart of the test rig is presented in Figure 1. The projectile can be injected into a heating zone by turning the flow through a three-way valve. After passing the heating zone the projectile will be recirculated to a transparent part to confirm that it is not stuck anywhere in the rig. Thereafter by opening a two-way valve, a small flow brings the projectile to its first position for the next injection.

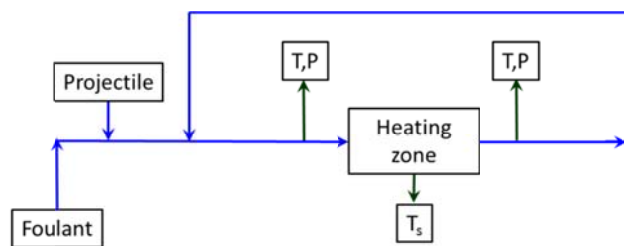


Fig. 1 Flow diagram of online cleaning rig.

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.

The rig contains a supply tank which is equipped with a cooling coil and 3 jacket heaters, each with a power of 500 W (1500 W) to adjust the bulk temperature of solution to a

set 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 majority of those in operation in industry. The intended operating conditions are listed in Table 1.

Table 1 Operating conditions



Variable	Range
Bulk temperature	40°C
Velocity	0.8 m/s
Chemicals	CaSO <sub>4</sub>
Concentration	4 g/L
Max. surface temperature in tube	135°C
Inside diameter of tube	20.0 mm
Min. projectile interval	2.5 Inj./Min.
Maximum heat flux	570 kW/m <sup>2</sup>

For monitoring fouling inside the tube, two thermocouples were inserted in the wall of the pipe. The Wilson-plot 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.

### Specifications of Projectiles

Two types of projectiles are used in this investigation as specified in Table 2. The projectiles are of 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 crystals. P02 was 10% bigger and harder to produce more shears to remove deposit when the fouling rate is relatively high.

Table 2 Specifications of used projectiles

Projectile		
ID	P01	P02
Diameter (mm)	21	22
Type	Sponge-ball	Sponge-ball
Stiffness	Flexible, soft	Flexible, hard

### 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 presence other ions thus demineralized

water with a conductivity of 50  $\mu\text{S}/\text{cm}$  is used. Since calcium sulphate crystals do not dissolve easily in water thus calcium nitrate tetrahydrate ( $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ) and sodium sulphate ( $\text{Na}_2\text{SO}_4$ ) were dissolved in water to produce calcium sulphate crystallizing onto inner hot surface of the tube [5].

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

15 L calcium nitrate tetrahydrate and 15 L sodium sulphate solutions are heated to  $40^\circ\text{C}$  in a separate thermostat tanks. Some minutes before the surface temperature reaches its set temperature, these two solutions are added into the supply tank. During the experiment, the concentration of  $\text{CaSO}_4$  is measured by EDTA titration and controlled by addition of respective solutions. The titration is done 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 has to be added into the supply tank.

### Data Reduction

For the determination of heat transfer coefficient, data such as bulk temperature (input flow), output temperature, flow velocity and inner surface temperature is required. Inner surface temperature could be calculated using two inserted thermocouples in the middle of wall pipe. The exact positions of these thermocouples toward inner surface were calculated with the 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. To characterize the deposition process thus fouling resistance  $R_f$  can be calculated according the overall heat transfer coefficients at clean and fouling conditions.

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

where  $U_f$  and  $U_c$  are the overall heat transfer coefficients under fouling and clean conditions.  $U_f$  is measured from the following equations:

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

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

It is imperative to mention that fouling spots on the tube surface has also a direct effect on the surface roughness; this roughness leads to increased turbulence. Sometimes when the first crystals are formed then the surface roughness increases. This in turn may result in the boundary layer to be agitated thus the heat transfer coefficient may even be higher than those under clean conditions. As a result, a negative fouling resistance would be expected.

## RESULTS AND DISCUSSION

Fouling is usually the net product of difference between the deposition and removal rates. While the first mainly depends on the driving forces that force precursors to move and attach to the surface, the latter dominantly due to the shear forces exerted by the fluid flow. The presence of particulate solids in the crystal lattice of the fouled layer, the increase of the thickness of the deposit and thermal stresses due to temperature gradients/transients make the fouling layer more fragile and accelerate the removal rate. Therefore the net rate of increase of the fouling layer can be formulated as:

$$\frac{d m_f}{d t} = \frac{d R_f}{d t} (\rho_f \lambda_f) = \dot{m}_d - \dot{m}_r \quad (4)$$

Subscripts “d” and “r” refer to deposit and removal, respectively. In this equation,  $\dot{m}_r$ , removal rate, is a function wall shear stress, and strength of deposit layer to the surface, thus:

$$\dot{m}_r = \frac{C \tau m}{\psi} \quad (5)$$

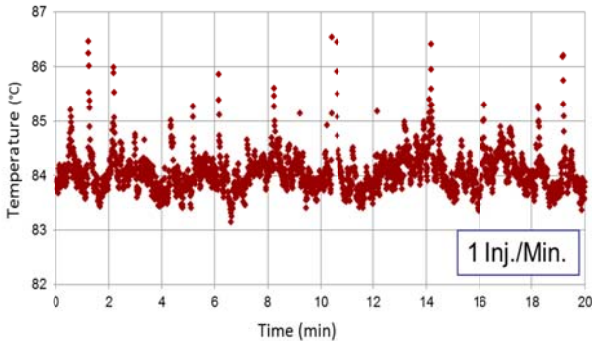
where  $\tau$  is the wall shear stress,  $\psi$  is the strength of scale factor and  $C$  is a proportionality constant. Field data and laboratory findings suggest that for instance in refineries, asphaltenic fouling at crude oil preheat train conditions can be mitigated when the wall shear stress exceeds approximately 10 Pa and is significantly suppressed when the shear stress at the wall surpasses roughly 15 Pa [6]. Nevertheless these shear stresses correspond to a velocity range that may not practically attainable. For a projectile, the rate of removal should be greater than the net rate of deposit formation in order to maintain the heat transfer surface clean:

$$\frac{d m_{r, \text{projectile}}}{d t} > \frac{d m_f}{d t} \quad (6)$$

Mohammadi and Malayeri [7] calculated that soft balls, with similar sizes presented in this paper, would typically exert a shear stress ranging from  $10^3$  to  $10^5$  Pa on the surface. This is by far is too much high to any shear stress that can be exerted by the fluid. Nevertheless this would only mitigate fouling is the projectiles are injected while the surface is still clean. Once deposit forms on the surface then it may require much higher shear stress to remove it. More work is currently underway by the author to determine the required force to remove a certain layer of deposit layer.

In this study, the first attempted projectile was P01. It is made of spongy material and quite soft. The projectile has a nominal diameter of 21 mm which 5% larger than the pipe inner diameter. It is first examined at clean conditions to discern if there is any improvement in heat transfer when the projectile agitates the boundary layer. Figure 2 illustrates typical variation of the surface temperature (interface between the surface and bulk) when P01 is injected every minute. As it can be seen the surface temperature is fluctuating around  $3^\circ\text{C}$  when the

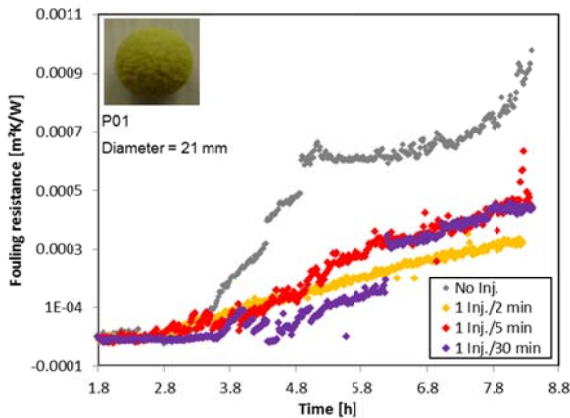
projectile is injected thus improvement in clean heat transfer coefficient is only marginal. This has evidently been shown in Table 2 which confirms the maximum clean heat transfer coefficient is increased by only 2% when two P01 are injected every minute.



**Fig. 2** Variation of surface temperature vs. time for an injection of projectile per minute.

Table 2 Variation of velocity, clean heat transfer coefficient and heat flow for different injection frequencies.

	v (av.) (m/s)	$U_c$ (av.) (W/m <sup>2</sup> ·K)	Q (av.) (W)
No projectile	0.815	7873	3621.8
1 Proj./Min	0.814	7969	3642.5
2 Proj./Min.	0.826	8051	3624.7

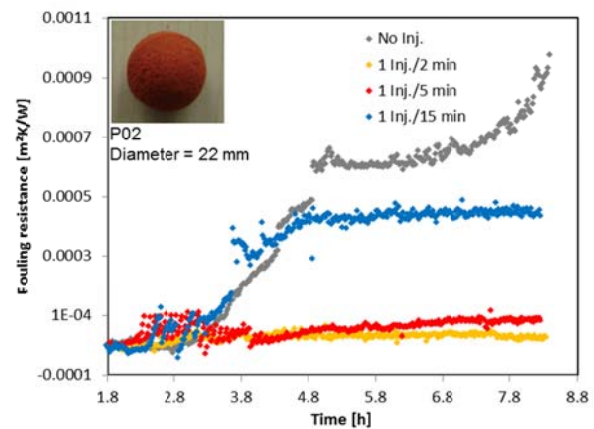


**Fig. 3** Impact of projectile P01 on deposit mitigation for different time intervals.

Figure 3 presents fouling experimental results without and with projectiles at different time intervals. The injection intervals were every 2, 5 and 30 minutes. Overall as expected, smaller injection intervals correspond to a better efficiency in terms of fouling mitigation. However, the pipe cannot be kept entirely free from deposit even with an interval of injecting P01 every two minutes. In this case, the fouling resistance is reduced to about a third of the value for no injection for similar time. These results also imply

that when the deposit is formed on the surface then the projectile can no longer take it away from the surface.

The experimental results for P02 for injection intervals of 2, 5, and 15 minutes are presented in Figure 4. Up to an interval of 1inj./5 min the pipe surface remains largely free from deposits during the run. For an injection of 1inj./15 min the fouling layer starts to grow. Figure 4 also shows that 1inj./5 min would be an optimum interval to keep the pipe in an acceptable level of cleaning of about one tenth compared with no injection. It is still a question how this result would be comparable to industrial scale. Nevertheless considering that injection decreases the fouling resistance by 1/10 than without injection, the size of heat exchanger also would be much smaller for construction. Thus the present results would have impact on exchanger energy recovery, independent of duration of experiments and injection interval.



**Fig. 4** Impact of projectile P02 on deposit mitigation for different time intervals.

Worthwhile also to mention the faster initiation of fouling when projectiles are injected compared to those with no injection which can clearly be seen in Figure 3 and 4 for P01 and P02. The curve for no injection indicates that it takes at least 2.5 hrs before fouling resistance starts to increase while it is quicker with projectiles. This can be related to the micro scratches that projectiles generate on the surface which would then pave the way for faster crystal nucleation. This has been despite the fact that P01 was quite soft while P02 was harder to propel inside the pipe. Accordingly the deposit initiation started earlier for P02 compared to that of P01. One can also see that for P02 the fouling resistance increased initially where it remained close to zero for case without injection before decreases again. More experimental work is required in the early stage of fouling to understand why this should occur.

Not only the measurement of fouling resistance would dictate how effective the projectiles are at any specified injection interval but the fouled surface can also be examined after each run to see how deposition is developed across the pipe. After each experiment, inside the pipe was fully scanned and the sketch of covered areas by deposits is drawn. Fig. 5 shows typical sketches after experiment with P02. Obviously the lowest time interval of 1inj./2min cleans the pipe at best,

though the deposit cannot be completely removed. In particular the projectile was able to take away deposit where it meets first while leaves behind more deposit at the end of heating zone (see Figure 5a). Furthermore, for longer injection intervals, more deposits remain. For instance, with an interval of 1inj./15min, only parts of the fouling layer are removed (see Figure 5b). It is also imperative to note for P01 at all intervals the deposit layer had fully covered the heating zone.

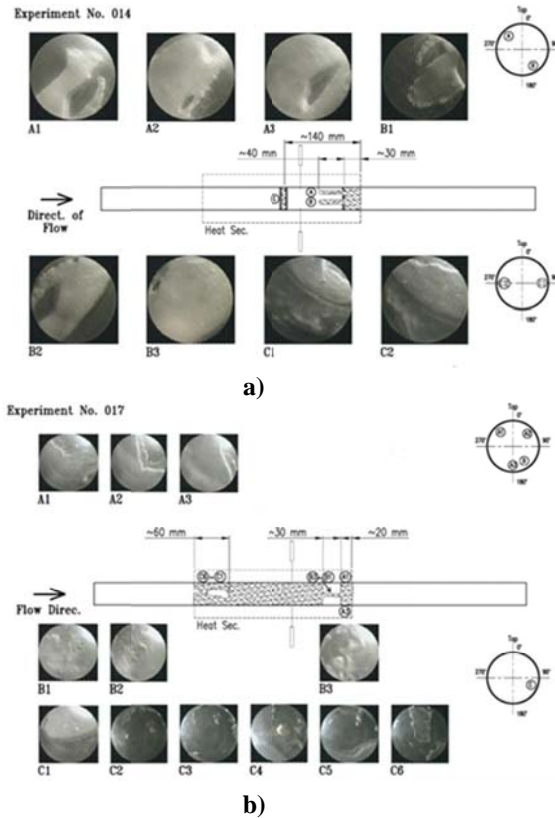


Fig. 5 Mapping of deposit layer for P02 for a) 1inj./2 min and b) 1inj./15 min.

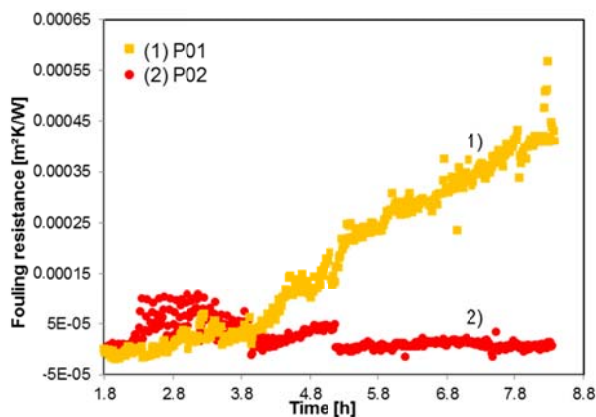


Fig. 6 Comparison of projectiles P01 and P02 for an injection interval of 1inj./5min.

Furthermore, the effectiveness of P01 and P02 are also compared together as presented in Figure 6 under similar operating conditions for an interval injection of 1inj./5min. P01 and P02 are sponge-type projectiles with diameter bigger than the pipe thus they are flexible to be deformed and passed through the pipe. P02 (D=22 mm) is harder and bigger than P01 (D=21 mm). The results show that P02 performs far better in keeping the surface clean than P01. Larger diameter and harder feature of P02 which correspond to more exerted shear stress should be accounted for the better performance of P02.

## CONCLUSIONS

Comparative investigation of various projectiles for fouling of calcium sulphate was performed inside a heated tube. Two different types of spherical projectiles were studied. The experimental results show that larger and harder sponge balls are more effective to maintain the surface clean than smaller and softer type only if they can be propelled inside the tube. In both cases also the initial deposition of crystallization was faster perhaps due to the scratch of the surface in micro-scale when projectiles are injected.

## ACKNOWLEDGEMENTS

The author gratefully acknowledges the financial support of the European commission for granting project Clean-Ex (project number 227462). R. Preimesser and M.R. Jalalirad are also contributed to this work of which the author wishes to thank.

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