

A CRITERION FOR THE SELECTION OF PROJECTILES FOR CLEANING TUBULAR HEAT EXCHANGERS

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ABSTRACT

Various types of projectiles are available in the market with different shape, size, texture, stiffness and material for online cleaning of tubular heat exchangers. Perhaps the largest group by far is the one with spherical shape. There exists nevertheless no publication in open literature to recommend the optimum physical properties in terms of size, and stiffness that would influence the cleaning action best. This study proposes a mechanistic criterion to define how to select an efficient projectile based on contact area and exerted shear force that a projectile would have when it is propelled through a tube. The criterion is examined for a number of spherical projectiles of various sizes and stiffness to appraise its reliability and functionality. To do so, the stiffness of projectiles is firstly measured and secondly numerous fouling experiments are carried out in which CaSO₄ is used as foulant, and a plain tube as the heat transfer surface. The resultant criterion shows the domain of projectile sizes that would best clean the surface for a specified stiffness and vice versa.

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 shell and tube heat exchangers. It is largely favored due to its long performance history, relative simplicity, and its wide temperature and pressure design ranges [1]. 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, such as loss of heat transfer, under-deposit corrosion, increase pressure loss and flow mal-distribution.

Among different mechanical mitigation techniques, projectiles of different shapes e.g. sponge balls can be propelled through the heat exchanger tubes to mitigate deposition. Projectile cleaning is ideal as it can be applied in 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. The advantage of this method is that the projectiles can

effectively mitigate fouling thus provide stable operation but limited to aqueous systems at temperatures below about 120°C, due to the stability of the projectile material [2]. Nevertheless, the experimental data about the performance of various projectiles is scarce and non-conclusive which otherwise would be needed to recommend the optimum physical properties i.e. size, and stiffness that would best influence the cleaning action [3-4].

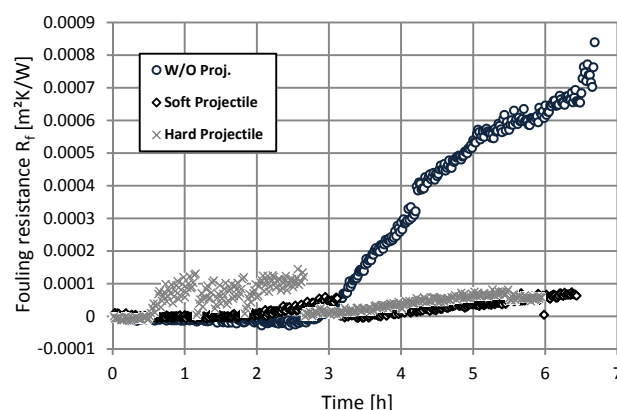


Fig. 1 Comparison the cleaning performance of two soft and hard projectiles for similar operating conditions. Bulk temperature 40°C, surface temperature 71°C, fluid velocity 1.3 m/s, CaSO₄ concentration 4.6 g/L and injection interval of 5 minutes [5].

It has long been asserted that harder projectiles would better clean the surface. Müller [5] though questioned such assertion when two projectiles of different stiffness were examined at the same operating conditions. Figure 1 typically illustrates the cleaning performance of two projectiles which one is hard (P12, diameter of 20.2 mm) and can exert 932 kPa shear force. Throughout the attempted fouling runs for both projectiles, the injection rate was kept the same every 5 min in the early stage and the induction period [5].

The softer one (P02, diameter of 22.0 mm) exerts only 75 kPa [5]. More details about these specific projectiles will be provided in the following sections. The figure underlines that softer projectile keeps the tube somewhat cleaner under similar operating conditions, especially at the early stage of fouling. This indicates that the cleaning performance does

not have any relation to the exerted shear force. Moreover the harder projectile initially facilitated deposit formation peculiarly compared to one that no projectile is used.

Jalalirad and Malayeri [6] showed that size of projectiles plays an important role to provide a stable contact with the tube under flow propulsion, but their optimum size, stiffness and subsequent relation to cleaning are still to be addressed. The present study endeavors to develop a simple, robust criterion for the selection of suitable projectiles in terms of stiffness and size. To do so, two distinct but inter-related experiments are carried out namely i) stiffness tests and ii) fouling test rig to examine various resultant criterion under harsh fouling environment.

EXPERIMENTAL SETUP AND PROCEDURE

Fouling Setup

A test rig is designed and constructed to investigate the on-line cleaning action of projectiles in tubular conduits during crystallization fouling. Details about the test rig, preparation of solution, experimental procedure and data reduction can be found elsewhere [2, 7, 8]. The test rig is designed such that projectiles can be propelled at different injection rates and velocities during fouling runs. A flow diagram of the setup is presented in Figure 2. The test rig consists mainly of a supply tank, a 3 hp centrifugal pump, heating zone with a tube having an inner diameter of 20 mm, a projectile injection system and a transparent part made of glass pipes to ensure the return of projectiles to the injection point. The CaSO₄ solution is pumped from the supply tank to the heating zone, i.e. the heat exchanger, via the centrifugal pump and then is returned to the supply tank.

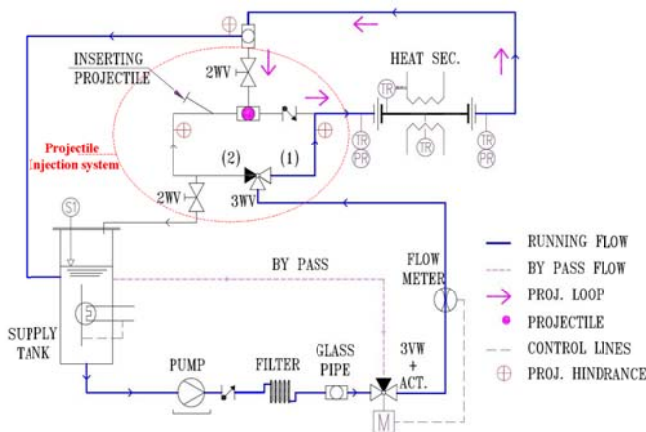


Fig. 2 A schematic of the experimental setup equipped with the projectile injection system

The heating zone also contains a circular tube heated directly from outside via an electrical heater of a maximum power of 10 kW. Heat is transferred from the electrical heater to the CaSO₄ solution passing through the heated tube. The projectile can be introduced into the heated tube by turning the flow to the heated tube. The projectile is then re-circulated to a transparent section to confirm that it is not stuck anywhere in the test rig. This is done by opening the

two valves, such that a small flow brings the projectile to its first position for the next injection.

The fouling process is characterized by the fouling resistance R_f , which is calculated from the overall heat transfer coefficients at clean (U_c) and fouling (U_f) conditions as:

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

The overall heat transfer coefficient U is also calculated from the following equation,

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

The wall temperature of tube T_w is where the thermocouples are embedded. The surface temperature T_s is calculated by the Wilson-plot [9].

Cleaning Efficiency (E)

When different projectiles are used to mitigate deposit formation, a parameter is required to compare results rigorously. Through the observation of the experimental fouling resistances versus time only the overall quality of projectile cleaning could be obtained, but there is not any quantitative value to say how better a projectile is when compared to others. The cleaning action of projectiles normally depends on their type in terms of size, stiffness and texture and the injection rate. Thus the cleaning efficiency is defined to quantify the performance of various projectiles. It is based on the average fouling resistance of tube with to without (w/o) injections. Considering a point at a given time of experiment, the efficiency would be the area below the curve of fouling resistance vs. time, with and without (w/o) injection (see Figure 3).

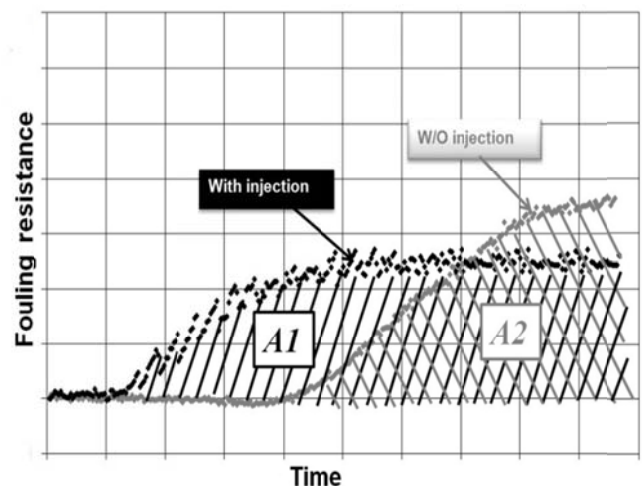


Fig. 3 Efficiency (E) of projectile cleaning.

Thus

$$E = \left(1 - \frac{A1}{A2}\right) \times 100 \quad (3)$$

Where E is the efficiency, A1 the area below the curve of fouling resistance vs. time when the projectile is injected and A2 is the area when it is not injected.

$$A1 = \int_0^t R_{f,w}(t) dt \quad (4)$$

$$A2 = \int_0^t R_{f,w/o}(t) dt \quad (5)$$

Here $R_{f,w}$ and $R_{f,w/o}$ are fouling resistances which can be determined from Eq. 1. If one assumes that the difference of surface temperature under fouling and clean condition is linearly proportional to fouling resistance then:

$$\frac{dR_f}{dt} \sim \frac{d(T_{s,f} - T_{s,c})}{dt} \quad (6)$$

This equation is driven based on linear relation between the surface temperature and fouling resistance, thus considering Eqs. 1 and 2, A_i and Q are constant for this series of experiments and only $T_{s,f}$ varies

This, in turn, results in

$$E = \left(1 - \frac{\sum_{i=0}^n (T_{s,f,w,i} - T_{s,c})}{\sum_{i=0}^n (T_{s,f,w/o,i} - T_{s,c})}\right) \times 100 \quad (7)$$

Where $T_{s,c}$ and $T_{s,f,w}$ denote surface temperature at clean and fouling conditions with injection and $T_{s,f,w/o}$ is surface temperature at fouling condition w/o injection. Moreover “i” counts the number of recorded data during the experiment. If $E = 100\%$, then it corresponds to utter and perfect cleaning of the surface by the projectile. For appreciable cleaning it could be in a range of 90-99% and for a good cleaning within the range of 70-89%. However, for values less than 70%, one should not bother to use the projectile in question as injection would only intensify fouling nucleation and make the induction period much shorter [7,8]. This implies that mitigation should be profound at the early stage of fouling process otherwise the act of projectiles would be counterproductive resulting in an intensified deposition as illustrated in Figure 1. It is also imperative to note that sometimes efficiency could be negative, even less than -200%. This dominantly occurs for loose projectiles and the ones with exact size of tube inner diameter.

Stiffness Measurement

A selected number of projectiles are examined at the Institute of Polymer Technology (IKT), University of Stuttgart to have their stiffness measured. Based on standard test procedure for such measurement as listed in Table 1, five pieces of each P01, P02 and P12 having different stiffness and sizes are selected for the tests. P01 is soft with a diameter 5% bigger than tube. P02 is harder but not as much as P12 with a diameter 10% bigger than tube. P12 was the hardest one thus its size could not larger than 1% of inner tube diameter. Based on assortment of projectiles

type, P01 and P02 are referred as soft and P12 as hard projectiles. They are then tested by a Zwick universal stiffness testing machine (model ZPM 1455). For the stiffness test procedure which is recommended by IKT, in the range of $\pm 10\%$ of projectile sizes, stiffness would be independent of diameter.

The tests are conducted such that the projectiles are clamped then loaded from above with a plate (see Figure 4). This is carried out through conditions listed in Table 1. Percentage of deforming as deformed diameter per initial diameter versus applied force is plotted for each projectile. Then the applied force for 50% of deformation is reported as a measure to explain the stiffness. These results in linear range of curves are much reliable. The parameter α represents the relation of force and deformation:

$$\alpha = \frac{x}{\varepsilon} \quad (8)$$

where:

x = Average force of each attempt on projectile [N]

ε = Deformation [%]

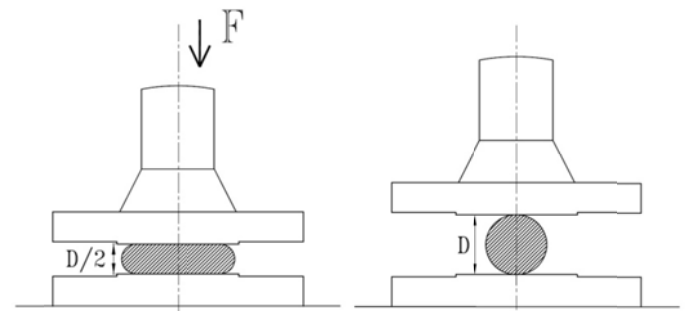


Fig. 4 The arrangement of the stiffness measurement.

Table 1 Procedural settings for stiffness tests.

Parameter	Setting
Test standard	DIN EN ISO 3386-1
Climate	DIN EN ISO 291-23/50-2
Sample pretreatment	Storage in standard atmosphere DIN EN ISO 291-23/50-2
Force transducer	1 kN
Transducer	Traverse
Sample holder	Plates
Test speed	100 mm/min
Preload	0.5 N

EXPERIMENTAL RESULTS

Stiffness Tests

The stiffness tests are intended to provide information on how deformation takes place when curves for load versus deformation are plotted. Projectiles were loaded until a compression of 50% is reached, meaning the projectiles retained 50% of their initial diameter at the end. Accordingly the force exerted on the projectile over

deformation has an approximate linear function, as shown in Figures 5-7. As five samples of each projectile are tested then each plot contains five curves.

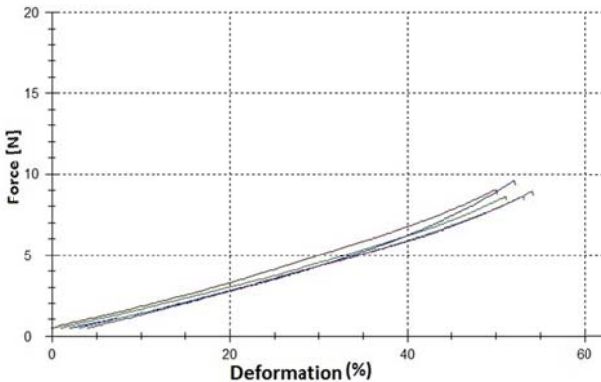


Fig. 5 Stiffness test for P01.

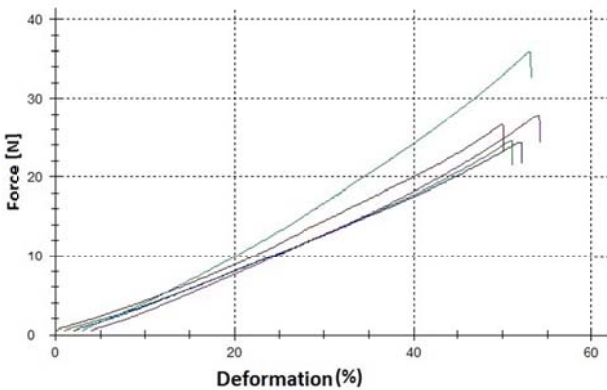


Fig. 6 Stiffness test for P02.

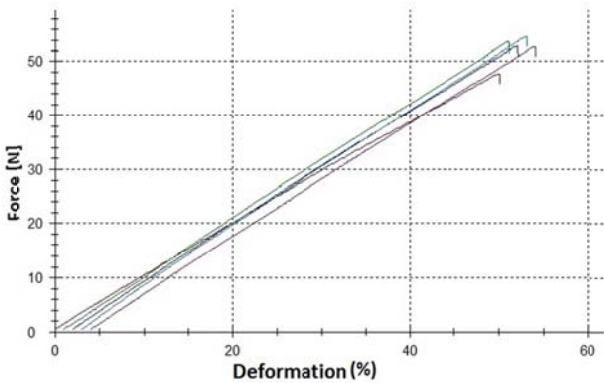


Fig. 7 Stiffness test for P12.

In these figures, the gradual increase in loaded force to 50% deformation reflects the projectile stiffness. For rubber projectile of P12, forces end up ranging from 48 to 54 N. Soft sponge projectile of P01 has the weakest stiffness, as forces range from 6 to 10 N. Sponge ball P02 is the medium among the three attempted projectiles with forces of 22 N to 24 N. The loaded force stops pressing the projectile further when deformation is beyond 50% the releases. This results in small abrupt drops at the end of curves. The average deformation results of each 5 pieces are listed in the Table

2. The table shows that P02 and P12 are 3.1 and 5.8 times harder than P01 while P12 is only 1.9 harder than P02.

Table 2 Comparisons of stiffness factor (alpha) for different projectiles.

Stiffness factor (α)	Value [$\frac{N}{\% \text{ deforming}}$]	Magnitude to others
α_{P01}	0.178	1
α_{P02}	0.558	$3.1 * \alpha_{P01}$
α_{P12}	1.040	$5.8 * \alpha_{P01}$ $1.9 * \alpha_{P02}$

The results show for the same force exerted, the P12 has the smallest deformation while P01 has the most severe deformation. In comparison with the tube inner diameter (20 mm) the maximum deformation can be as much as 10%, which shows the testing range of 50% (D/2) is definitely in the range of practical application. This means that the deformation of 50% in stiffness tests is in the range of maximum allowable deformation that practically happens in tubular heat exchangers. The parameter α presents the relation of each projectile between average pressing forces with five balls, when the deformation reaches 50%.

Projectile Efficiency

15 experiments with projectiles of different stiffness and sizes are carried out under fouling conditions. Different injection intervals have also been attempted to find out the optimum diameter and stiffness which corresponds to the best cleaning performance. The summary of resultant findings is given in Table 3.

Table 3 Efficiency of various projectiles for different injection intervals. Bulk temperature 40°C, surface temperature 71°C, and CaSO₄ concentration 4.6 g/L.

Proj. ID	Diameter mm	Stiffness [$\frac{N}{\% \text{ deforming}}$]	Contact area mm ²	Applied τ Pa	E 5 min	E 10 min	E 15 min
P01	21.0	0.178	132.1	14,199	40% v=0.8		
P02	22.0	0.558	277.3	75,010	80% v=0.8	60% v=0.8	10% v=0.8
P04	19.8	1.040	loose	0	-50% v=1.3	-300% (Stuck) v=1.3	
P05	24.0		609.9		Projectile was torn after 29 injection		
P11	20.0	1.040	negligible	negligible	0% v=1.3	-210% (Stuck) v=1.3	
P12	20.2	1.040	25.4	932,313	60% v=1.3	-60% v=1.3	-220% V=1.3

The reported contact areas in this table are simply measured in a transparent tube with similar inner diameter to that of the metal tube (20.0 mm) which is used in fouling experiments. Note that the test procedure for measuring the exerted shear on the tube wall, provided in this table, is fully explained elsewhere [6].

Evidently as it can be seen, P02 has the best efficiency compared to others. Hard projectiles of P04, P11 and P12 with the same material but different sizes of 19.8, 20.0 and

20.2 mm are also examined. Nevertheless only P12 which has a small contact with pipe had better efficiency. Loose projectiles as well as those having similar size to the inner tube diameter are expected not to clean in an appreciable manner. This also means that they would even intensify deposit formation [2] and also they are liable to get stuck in the tube. P05 is a stereotype soft projectile and 20% larger than tube inner diameter but its life time was short because of severe deformation after passing through the tube. This indicates that to get stuck would not be a problem for soft projectile as much as hard projectiles even if they are 20% larger than the inner tube diameter.

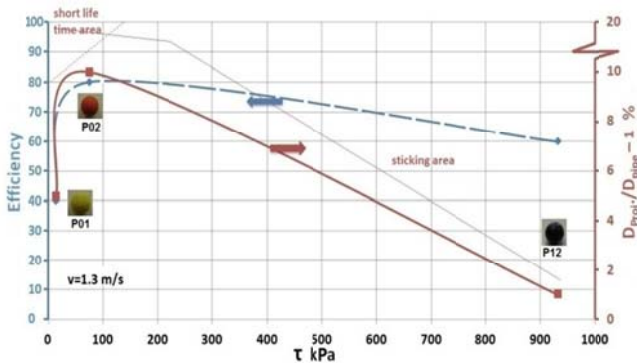


Fig. 8 Efficiency based on the exerted shear [6] and contact area, resulted from Table 3.

The experimental results for P01, P02 and P12 are also presented in Figure 8 in terms of efficiency versus exerted shear force. The figure shows applying a higher shear force does not always mean the projectile has a better cleaning performance. Quite opposite, it is the projectile size that may have much higher impact though. Size implies the extent of contact area between the projectile and the tube. In Figure 8, the positions of three projectiles based on size or efficiency versus applied shear force are specified. These three projectiles are samples of soft (P01), medium (P02) and hard (P12), respectively. As it can be seen, the most efficient projectile is P02 which is represented by the dashed curve to “efficiency axis” on the left side. The optimum size also is referred by the solid curve to the right axis to show how much the projectile is bigger than then tube. The figure also shows in what areas the projectile will have a short life time and where it would get stuck in the tube for a fluid velocity of 1.3 m/s. A prominent sample for a short life time projectile is P05 which is 20% bigger than the tube.

The lines in this figure are based on experimental trials where one projectile for “short life time area” and 5 projectiles for “sticking area” were used. The reason for only one run for short life time area is due to lack of having varieties of different projectiles and experiment costs which otherwise would be required to conduct such tests as the projectiles should be very soft and big to be located in this area. Nevertheless numerous experiments to identify the sticking area were conducted for a number of projectiles. Thus the lines in Figure 9 typically show the safe margin to avoid sticking for soft projectiles with respect to hard ones.

DISCUSSION

The size of hard projectiles is usually not bigger than 2% of size of tube inner diameter and the minimum required velocity to push them in tube is more than 1 m/s [6]. Contrariwise, soft projectiles can even be larger i.e. 5% which can be propelled in velocities less than 1 m/s [6]. Jalalirad and Malayeri [6] showed the important point to discriminate these two groups is the extent of their contact with the tube. In a mechanical test, hard projectiles exert much higher shear force even 10 times bigger than soft projectiles though their cleaning is not terribly better than softer ones. The reason is attributed to the non-stability in contact with the tube. Hard projectiles exert much higher shear force on surface in mechanical pushing, but under the propulsion force of flow it does not apply a remarkable shear due to less and unstable contact area between projectiles and the tube. This can be represented by a parameter called stability factor, Z , which is less than 0.2 for hard projectile and between 0.6 - 0.8 for soft projectiles [6]. It has also been shown the “ Z ” factor is a function of stiffness [6]. Another disadvantage of hard projectiles is probability in getting stuck in the tube which is more likely than for a soft projectile. At the same time, projectiles could not be too soft as well, since they cannot exert enough shear for cleaning. This means there is an optimum point for the stiffness to have the best cleaning footprint.

Apart from stiffness, another parameter which plays an important role for cleaning is the projectile size. When the projectile is big, it could have more contact with the surface thus better cleaning is expected. Nonetheless, there are also some limitations in size too, i.e. sticking probability and the life time of projectiles under continuous deformation. If they are hard it is more likely to get stuck and when they are soft then deform severely as they pass through the tube and their life-expectancy would be shorter. This implies that there is an optimum area for projectile size as well. Attempts were consequently made to develop a plot to select the most efficient projectiles based on the stiffness and size. Whereas the exerted shear force by projectiles is directly related to the stiffness, the data on horizontal axis were substituted with the stiffness. It gives more engineering sense and it could be independent of any other tests.

Figure 9 shows the optimum size and stiffness for the best cleaning performance. It also underlines in what area the projectile is expected to have a shorter life time, and also the margin where the projectile may get stuck. If the projectile is as hard as P12 it would get stuck if it is just 2% bigger than the tube. This margin for sticking is important and it should be wide enough, because the surface of a new tube is smooth and projectile may passes easily but the problem would appear when the deposit forms resulting in a roughened surface. For harder projectiles it is just 1% of the tube diameter, while it could be 20% for softer projectiles. The specified box of ABCD signifies the optimum size and stiffness. It means the projectiles 10% bigger than the tube could be the most efficient if they are hard enough to deform just 1% under a 0.6 N force. In general this figure shows that using soft projectiles is more advantageous. The proposed criterion to show the influence of cleaning

performance of projectile in Figure 9 is a compromise based on Figure 3 and Eq. 3.

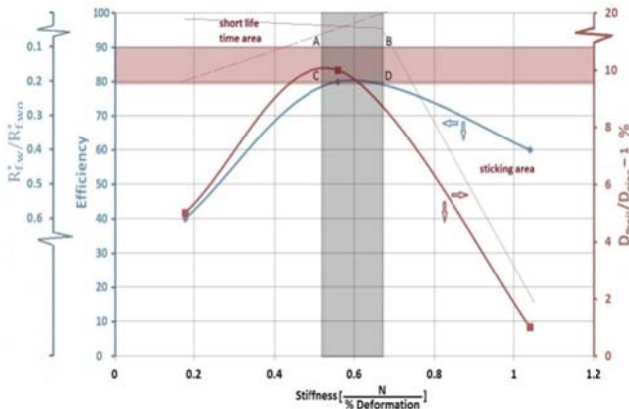


Fig. 9 $R_{f,w}^*/R_{f,wo}^*$ and Efficiency based on stiffness and contact area.

Another criterion to discern how efficient a projectile is the ratio of fouling resistance with and without projectile injection in asymptotic region of fouling process ($R_{f,w}^*/R_{f,wo}^*$). In this investigation the tube diameter, heat flux, velocity of flow and size of projectiles are an order of magnitude of those in industries. In cases that this ratio is less than 0.2 it could be considered somewhat the most efficient cleaning in industry. It is predicted that this ratio is depended upon the mechanism of deposit formation, velocity of flow and rate of injection hence it could be easily extended to industrial scale. Asymptotic fouling resistance for many chemicals and water services is reported in standard design books. This value can somewhat determine the size and construction cost of heat exchangers. Thus $R_{f,w}^*/R_{f,wo}^*$ can give a better sense to heat exchanger engineers. Nevertheless considering this point that injection decreases the fouling resistance by 80% ($R_{f,w}^*/R_{f,wo}^*=0.2$), the size of heat exchanger also would be smaller for the construction even by 15% [10].

CONCLUSIONS

Contact area of projectiles and the tube inner wall and their stiffness are the most important parameters that would determine the extent of projectile cleaning. Stiffness produces shear force and projectile size contact with the tube. To have the best cleaning performance, there is a trade-off between the projectile size and stiffness. The best size would be 10% bigger than the tube and the optimum stiffness is 1% deformation under a 0.6 N force. Using projectiles out of this domain may be problematic. Bigger and softer projectiles cannot stand against long time injections thus their life-expectancy would be short. Simultaneously harder projectiles are more likely to get stuck. $R_{f,w}^*/R_{f,wo}^*$ (ratio of fouling resistance with and without injection) can give a better sense for cleaning the heat exchanger and $R_{f,w}^*/R_{f,wo}^*$ could be decreased by 80% if a suitable projectile of the right size and stiffness is selected.

NOMENCLATURE

A_i	Inner surface area of the heated tube
$A1$	Area under the curve of fouling resistance vs. time with projectile
$A2$	Area under the curve of fouling resistance vs. time without projectile
c_p	Specific heat capacity, J/kgK
E	Efficiency, -
i	number of recorded data during experiment
\dot{m}	Mass flow rate, kg/s
n	Total number of logged experimental data
Q	Rate of heat transfer, W
q	Heat flux, W/m ²
R_f	Fouling resistance, m ² K/W
$R_{f,w}^*/R_{f,wo}^*$	Ratio of asymptotic fouling resistance with and w/o projectile
T_b	Bulk temperature, °C
T_i	Fluid inlet temperature to the heated zone, °C
T_o	Fluid outlet temperature from the heated zone, °C
T_s	Surface temperature, °C
$T_{s,c}$	Surface temperature at clean condition, °C
$T_{s,f,w}$	Surface temperature at fouling condition with projectile, °C
$T_{s,f,w/o}$	Surface temperature at fouling condition without projectile, °C
t	time, s
U	Overall heat transfer coefficient, W/m ² K
v	Velocity, m/s
x	Average exerted force on the projectile [N]
α	Relation factor of force and deformation, N/percentage of deformation
ϵ	Deformation [%]

Subscripts

b	bulk
c	clean
f	fouling
i	inlet, inner
o	outlet
s	surface
w	with
w/o	without

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