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Cleaning action of spherical projectiles in tubular heat exchangers

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ABSTRACT

Projectiles of different properties, i.e. shape, materials, hardness, can be propelled through the heat exchanger tubes to mitigate fouling when used at the early stage of deposition process. In the present study, fouling experiments have been performed in which $CaSO_4$ was used as foulant and plain tubes as heat transfer surfaces. The rate of projectile injection was also varied to discern its impact on the cleaning. The experimental results showed that at fouling conditions, the inner layer of the deposit, i.e. near the heated surface, is sintered while the outer layer of the deposit, i.e. near the solution side, is porous and crystalline. As the fouling process reaches an asymptote, the whole fouling layer is sintered. Sintering changes the whole fouling layer to a robust and non-porous structure which does not allow the projectile to remove crystals from the deposit layer anymore. Two mechanisms are simultaneously dominant once projectiles are injected (i) sintering of the fouling layer near the tube surface and (ii) removal of precursors from the deposit layer near the solution side due to projectiles. If the removal rate is faster than the sintering rate then it is expected to end up with a very thin sintered layer and vice versa. Furthermore, using high injection rates will minimize the deposit thickness and once an asymptote is reached then it is not recommended to use projectiles anymore.

1. Introduction

Scale formation or crystallization fouling is defined as the precipitation of unwanted materials, originally dissolved in process fluids, on heat transfer surfaces forming an insulating layer. Scale deposits on heated surfaces are formed from salts whose solubility decreases with increasing temperature [1]. Fouling of heat transfer surfaces can cause serious operating and maintenance problems which would, in turn, result in enormous cost penalties [2–5]. In particular, in desalination plants, fouling can lead to inefficient operation and sometimes operation failure, causing even unscheduled shut-down for maintenance [6,7].

Many mitigation techniques have been developed to minimize and if possible to prevent fouling i.e. crystallization. Müller-Steinhagen et al. [8] have summarised the main methodologies for mitigation of fouling in industrial heat exchangers. They concluded that fouling, among various other approaches, can also 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 [9,10], e.g. sponge balls, through the heat exchanger tubes to remove deposits. Jalalirad et al. [11] performed a comprehensive set of crystallization fouling experiments with and without projectiles, and found that the cleaning effect of the projectiles is so strong at the early stage of the fouling process. They concluded that the structure, hardness, and morphology of the deposit layer are of prime importance.

Jamialahmadi and Müller-Steinhagen [12] and Esawy et al. [13] studied $CaSO_4$ deposition, as major fouling occurrence in desalination and power plants, on heat transfer surfaces during pool boiling. Jamialahmadi and Müller-Steinhagen [12] found that the density and thermal conductivity of the fouling layer increase with increased temperature of the heating element. In addition, Esawy et al. [13] showed 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. Malayeri et al. [14] performed similar experiments to [13] but for a tube bundle. They found that at higher surface temperatures the fouling layer is denser, harder, more compact and more adherent than those at lower surface temperatures. It can therefore be concluded that any change in the deposit layer structure can probably affect the fouling propensity and severity and may also the cleaning action of projectiles.

The present experimental study endeavours to examine the influence of the deposit layer structure on the cleaning action of projectiles. Fouling experiments have been performed in which $CaSO_4$ where used as foulant, plain tubes as heat transfer surfaces

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Nomenclature

Symbols

A_i	inner surface area of the heated tube
B	bias error
C	uncertainty
c_p	Specific heat capacity, J/kg K
$\dot{m}$	mass flow rate, kg/s
P	precision error
Q	rate of heat transfer, W
q	heat flux, W/m^2
R	thermal resistance, m^2 K/W
$\overline{R}$	average thermal resistance, m^2 K/W
R_f	thermal resistance of the fouling layer, m^2 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
$T_{FL,i}$	temperature of the inner surface of the fouling layer, °C
$T_{FL,o}$	temperature of the outer surface of the fouling layer, °C
t	time
U	overall heat transfer coefficient, W/m^2 K
δ	thickness of the FL, m
k	thermal conductivity of the FL, W/m K

Subscripts

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

Abbreviations

EDTA	ethylene-diamine-tetra-acetic
FL	fouling layer
HE	heat exchanger
inj	injection
MST	minimum sintering temperature
Proj	projectile
SEM	scanning electron microscope
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

and projectiles with different injection rates have been used to examine their influence on the cleaning of the deposit layer. The fouling resistance is measured continuously during the whole experiment. Samples of the fouling layers were also taken at the end of each experiment for analysis using the scanning electron microscope.

2. Experimental setup and experimental procedure

2.1. Experimental setup

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 three 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 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 2.5 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 [15] 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 doted 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 projectile used is a soft spherical sponge ball that has a diameter of 22 mm, which is 10% larger than the inner diameter of the heated tube. The diameter of the projectile has been selected to be larger than the diameter of the heated tube to produce enough shears to remove deposits and to wipe out nucleated crystals. The range of operating conditions that can be achieved by the test facility is given in Table 1.

2.2. Preparation of $CaSO_4$ solution

Calcium sulphate, which is used as foulant in this investigation, has an inverse solubility with temperature above 40 °C [16]. This solubility is strongly a function of the presence of other ions [17] in water, thus demineralised water with a conductivity of 50 μS/cm is used. Since calcium sulphate crystals do not dissolve easily in