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The impact of crystallization fouling on a microscale heat exchanger

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ABSTRACT

Due to their very high surface-to-volume ratios micro heat exchangers provide possible advantages in heat and mass transfer operations. Besides the potential of process intensification and low investment the process stability of these micro structured devices is a required criterion for industrial applications. Micro structured devices are very sensitive to unwanted deposition such as crystallization of inverse soluble salts on the surface (fouling). In general, fouling results in (i) an increase of the pressure drop, (ii) a decrease of the heat exchanger performance, (iii) a maldistribution of the flow in the micro structures and (iv) a change of the residence time behavior. This paper presents investigations about the impact of crystallization fouling on the heat transfer performance of a micro heat exchanger. Fouling experiments with calcium carbonate ($CaCO_3$) were analyzed regarding thermal and fluid dynamic behavior. The observed fouling developed heterogeneously from a supersaturated solution in micro channels and caused a decrease of the heat transfer performance and a strong increase of the pressure drop. The extracted fouling resistances R_f were in the range of 10^{-5}–10^{-3} $m^2\,K\,W^{-1}$. In general, the fouling behavior in microscale is comparable to that in macroscale.

1. Introduction

1.1. Micro heat exchangers

Micro heat exchangers are developed and manufactured from micro structured devices that in general are equipped with micro channels whose hydraulic diameters are less than 1 mm [1]. Fig. 1 shows a typical example of a cross flow micro heat exchanger (IMVT, KIT). Compared to conventional heat exchangers, micro heat exchangers have advantages concerning directed heating, short residence times and in case of a reactor a higher product conversion rate [2,3]. Therefore the use of micro heat exchangers is an appropriate instrument for process intensification due to high heat and mass transfer rates. A major requirement of many processes that can be realized with micro heat exchangers is their long term thermal stability and their cleanability. The application in chemical industries is still rare because micro structures are very vulnerable to corrosion and fouling. In order to avoid corrosion many heat exchangers are operated with pH values above 7 but crystallization fouling rates rise with higher pH values [4].

1.2. Crystallization fouling

Crystallization fouling is the unintended deposition of crystals on heat transfer surfaces and can cause severe damage to the heat exchanger and the connected equipment [5]. The fouling process considered here can be described as the heterogeneous crystallization of inverse soluble salts, e.g. $CaCO_3$ (limestone) and $CaSO_4{\cdot}2H_2O$ (gypsum), on the hot heat exchanger surface [6]. Furthermore crystallization fouling can be divided into the following periods: heterogeneous crystal nucleation, crystal growth, adhesion, removal and aging [7]. The main driving force for this crystallization process is the local supersaturation on the heat exchanger surface caused by the surface temperature T_w and concentration C. For electrolytes the level of supersaturation can be described with the saturation index SI (Eq. (1)) [8]. It is defined as the common logarithm of the ratio of the ionic activity product IAP and the equilibrium solubility product K_{sp}. For a supersaturation of the solution the saturation index must be greater than zero.

$$\mathrm{SI} = \log\left(\frac{\mathrm{IAP}}{K_{SP}}\right) = \log\left(\frac{\prod_1^i a_i}{\prod_1^i a_i^{eq}}\right) = \log(S(C, T_w)). \tag{1}$$

During nucleation and consecutive crystal growth an interface between the crystal and the heat exchanger surface is formed which causes the adhesion of the single crystals on the surface

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Nomenclature

A	heat transfer area (m^2)
a	activity, dimensionless
C	concentration (mol m^{-3})
c_p	heat capacity (kJ kg^{-1} K^{-1})
H_{ad}	adhesive strength (Pa)
h	heat transfer coefficient (W m^{-2} K^{-1})
IAP	ionic activity product, dimensionless
K_{sp}	equilibrium solubility product, dimensionless
M	mass flow (kg s^{-1})
$\dot{Q}$	heat flow (W)
R_f	fouling resistance (m^2 K W^{-1})
Re	Reynolds number, dimensionless
S	relative supersaturation, dimensionless
SI	saturation index, dimensionless
T_w	initial mean surface temperature (°C)
t	time (s)
t_D	residence time (s)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
x	thickness, m
λ	thermal conductivity (W m^{-1} K^{-1})
τ	shear stress (Pa)
$\Delta T_{\log}$	logarithmic mean temperature difference (K)

Subscripts

F	fluid
eq	equilibrium
f	fouled
i	encounter
in	inlet
ind	induction
out	outlet
0	clean
1, 2	sides

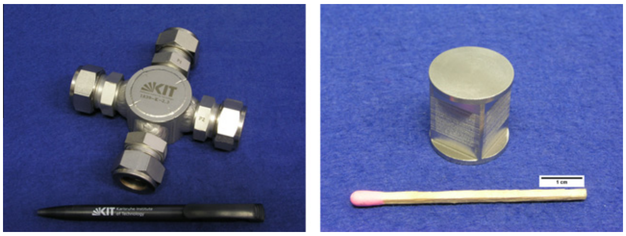

Fig. 1. Crossflow micro heat exchanger with a volume of 8 cm^3 (left), micro structured cores for crossflow micro heat exchanger of different sizes (right).

[9]. Fouling layers are built up of numerous single crystals. The more fouling deposit is formed the more the thermal characteristics of the heat exchanger change due to the insulating properties of the foulant and the contracting cross sections. In general, fouling results in a drastic decline of the heat flow for $\Delta T = (T_{out} - T_{in})$ = const. and thus of the heat exchanger performance. Hence, the fouling resistance R_f (Eq. (2)), which describes the change of the overall heat transfer coefficient U, can be used to describe the thermal impact of fouling. However, in some cases a rigorous model of the fouling resistance $R_f = x_f/\lambda_f$, especially for asymptotic fouling values, can be applied [10,11]. This is mainly the case when the film coefficients ($h_0 = h_f$ = const.) remain approximately constant under fouling conditions. According to [15] the change of the surface roughness due to fouling can be regarded in the film coefficient through the friction factor that is determined from pressure drop measurements. Fig. 2 shows a schematic diagram of the heat flow through a heat exchanger wall. In technical processes this is typically compensated by increasing the driving temperature difference to keep $\dot{Q}$ = const. In many cases this will accelerate fouling build-up.

$$R_f = \frac{1}{U_f} - \frac{1}{U_0} = \frac{1}{h_{f,1}} + \frac{x_{f,1}}{\lambda_{f,1}} - \frac{1}{h_{0,1}} + \frac{1}{h_{f,2}} + \frac{x_{f,2}}{\lambda_{f,2}} - \frac{1}{h_{0,2}}. \qquad (2)$$

Possible time dependent behaviors of the fouling resistance are shown in Fig. 3. In many cases two periods can be identified: (I) the induction period in which the heat transfer is not reduced significantly and (II) the layer growth period. In some cases an asymptotic behavior can be observed because deposition and removal rates become equal.

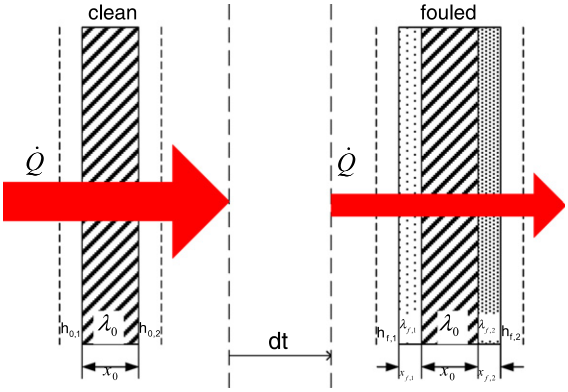

Fig. 2. Schematic diagram of the heat flow through a clean and a heat exchanger wall fouled on both sides.

Removal of fouling takes place when the shear stress introduced by the fluid flow exceeds the adhesive strength. In the long term, fouling deposit can undergo phase changes, compression of void spaces and other aging effects [7].

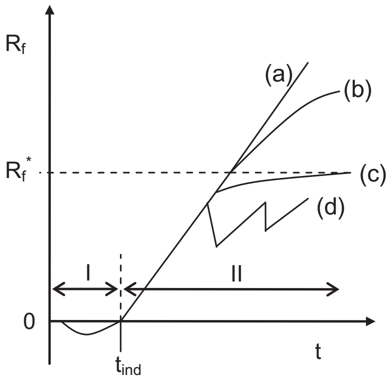

Fig. 3. Fouling resistance over time: I induction period, II layer growth period, (a) no removal, (b) descending build-up rate due to removal, (c) asymptotic behavior: deposition and removal rate become equal, and (d) saw tooth shape: removal of big fouling fractions.