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Mineral scale control in polymer film heat exchangers

Christian Dreiser, Hans-Jörg Bart*

University of Kaiserslautern, Chair of Separation Science and Technology, Gottlieb-Daimler-Straße 44, D-67663 Kaiserslautern, Germany

HIGHLIGHTS

- Crystallization fouling on polymeric heat transfer surfaces is studied.
- Scaling quantification is supported by an analysis of deposition kinetics.
- Correlations as functions of process conditions are developed.
- Results gain surface material selection and polymer heat exchanger design.
- Promising cleaning in place strategy is presented.

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ABSTRACT

Single salt deposition of $CaSO_4$ and $CaCO_3$ is studied on various polymeric heat transfer surfaces to gain a sound basis for novel polymer film heat exchanger (PFHX) design. Even at high overall heat transfer conditions (possible due to small wall thickness) the scaling quantity was found to be very low compared to a stainless steel surface and strongly dependent on the interfacial energy difference between polymer surface and deposit. The comparatively low scaling quantity is explained by an investigation of the $CaCO_3$-deposition kinetics, which reveals an activation energy that is 40% higher for the polyether ether ketone (PEEK) surface compared to stainless steel. The developed correlations for the quantity of crystallization fouling as a function of supersaturation and flow conditions can be applied in PFHX design and operation with regard to scaling mitigation. A breakup of the falling film results in significant crystallization fouling enhancement and should be avoided during heat transfer operation. The presented cleaning in place strategy for the PFHX concept is very promising and easily applicable, which contributes to the overall effectiveness of the apparatus concept.

1. Introduction

The understanding and mitigation of fouling and scaling in industrial heat transfer processes is of major interest in design of overall efficient equipment. The operational problems caused by heat transfer loss, increased pressure drop and flow maldistribution result in additional costs due to oversizing heat transfer area, energy losses and increased maintenance costs [1].

Polymer heat exchangers have been developed for example to condense corrosive media [2,3], designed as shell and tube heat exchangers and later as compact or foil heat exchangers [4,5]. Advantages of polymeric materials are a high chemical degradation stability, corrosion resistance and price stability, but usually they have very low thermal conductivities. However, the overall heat transfer coefficients are very low for existing polymeric heat exchangers (U_c = 150–250 W m^{-2} K^{-1}) as well as scaling and fouling resistances [6]. The overall heat transfer coefficients become similar to stainless steel when thin polymer films are installed as heat transfer surfaces in falling film processes.

Compared to stainless steel or Cu/Ni alloys wall thicknesses s of around 25 μm must be applied for most polymer films in order to compensate the resistance of heat conduction in falling film heat transfer processes. In that case the overall heat transfer becomes competitive with common plate heat exchangers (s = 1–2 mm). Christmann et al. [7] achieved high overall heat transfer coefficients of e.g. 3765 W m^{-2} K^{-1} at falling film evaporation by applying PEEK films (s = 25 μm). The good thermal performance is also a result of the spacer grid (transfers mechanical stress from buckling polymer film to the apparatus housing), which redistributes the liquid and enhances the falling film side heat transfer (see Fig. 1).

With a thermal conductivity of k = 0.25 W m^{-1} K^{-1} (without modifications) and high thermal and mechanical stability the PFHX can be applied at heat transfer processes such as thermal seawater desalination (ϑ < 80 °C, Δp < 80 mbar) [8], wastewater treatment

* Corresponding author.
E-mail address: bart@mv.uni-kl.de (H.-J. Bart).

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Nomenclature

A	heat transfer area, m^2
A	pre-exponential factor, $m^4\ mol^{-1}\ s^{-1}$
Bi	Biot number, –
c	concentration, $mol\ l^{-1}$
E_a	activation energy, $J\ mol^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
k_R	rate constant, $m^4\ mol^{-1}\ s^{-1}$
m	mass, kg
$\dot{m}$	mass specific rate, $kg\ s^{-1}$
M	molar mass, $kg\ mol^{-1}$
n	rotational speed, min^{-1}
U	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
$\dot{q}$	heat flux, $W\ m^{-2}$
R	molar gas constant, $J\ mol^{-1}\ K^{-1}$
R	thermal resistance, $m^2\ K\ W^{-1}$
R^2	coefficient of determination, –
Re	Reynolds number, –
s	wall thickness, m
t	experimental time, s
T	absolute temperature, K

Greek letters

$\Delta\gamma$	interfacial energy difference, $mN\ m^{-1}$
Δp	pressure difference, bar
Γ	falling film mass flow per unit of length, $kg\ s^{-1}\ m^{-1}$
ϑ	temperature, °C
ω	relative wetted area of heat transfer surface, –

Superscripts

*	asymptotic value

Subscripts

0	initial value
b	bulk
c	clean surface
C	crystal surface
d	deposition
f	fouled surface
ff	falling film
G	gas phase
in	inlet
S	solid surface
s	surface
w	wall

Abbreviations

PEEK	polyether ether ketone
PFHX	polymer film heat exchanger
PSU	polysulfone

or slightly corrosive environment in general. In such processes, however, crystallization fouling of inverse soluble salts like $CaSO_4$ and $CaCO_3$ is one of the major fouling mechanisms [9,10]. Investigations of $CaSO_4$-scaling on polymer surfaces performed by Dreiser et al. [11] showed a promising performance compared to stainless steel (Fig. 2).

Single salt scaling of $CaSO_4$ and $CaCO_3$ solutions is studied in the present work for various polymer surfaces compared to a benchmark material in heat exchanger design (stainless steel 1.4571), especially at high heat transfer conditions. The identified impacts of wall temperature, salt concentration and flow conditions allow a prediction of process related scaling mitigation for polymeric heat exchangers. An interfacial energetic relation helps to understand the specific polymer–crystal-interactions. A chemical-free and fast cleaning strategy for the PFHX apparatus concept is presented as well.

Fig. 1. View on the polymer film heat transfer surface supported by a point welded grid (30 × 30 mm).

2. Experimental

2.1. Materials and screening experiments

The thermoplastics PEEK and polysulfone (PSU) as well as their modifications are selected as potential heat transfer surfaces and were obtained by Victrex® Europa GmbH (PEEK) and Dr. D. Müller GmbH (PSU). As a benchmark material in apparatus construction, stainless steel 1.4571 (316 Ti) was used. The basic kinetics of crystallization fouling on various plane surfaces is investigated in a batch screening reactor with a clean heat transfer area of $A_c = 24\ cm^2$. Fig. 3 shows the scheme of the setup.

The screening experiments are carried out at constant bulk temperature ϑ_b and heat flux $\dot{q}$ adjusted with a power transformer. Initial wall temperatures are studied as well as initial bulk concentration c_0 of supersaturated salt solutions. The supersaturation of inverse soluble salts is achieved by merging stoichiometric amounts of dissolved single salts. The calcium sulfate solution is prepared with calcium nitrate tetrahydrate and sodium sulfate. The analog preparation of calcium carbonate solution is carried out by mixing chloride-dihydrate and sodium bicarbonate solutions. To prevent an impact of seed crystals the solutions are filtered before each experiment.

As a result of crystallization fouling of the inverse soluble salts on the hot heat transfer surface, the wall temperature will change over time and consequently the overall heat transfer coefficient. The actual overall heat transfer coefficient of the fouled surface U_f can be related to the overall heat transfer coefficient of the clean surface U_c to calculate the transient fouling resistance R_f as follows: