Published online www.heatexchanger-fouling.com

POLYMER FILM HEAT EXCHANGER FOR SEAWATER DESALINATION: PREVENTION AND CLEANING OF FOULING DEPOSITS

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ABSTRACT

Polymer film heat exchangers show a considerable potential as a cost-efficient apparatus for thermal seawater desalination plants. However, the occurrence of mineral scale formation on polymeric heat transfer surfaces requires basic investigations in order to improve existing design criteria. A polymer film heat exchanger (PFHX) concept, as well as the scaling affinity of the polymers compared to the benchmark stainless steel, is discussed. The scaling kinetics on polymer surfaces are slower compared to stainless steel, resulting in an extension of a save operation period before cleaning of about a factor of 10. Once the threshold of heat transfer due to fouling is reached, a fast cleaning of PFHX surface is accomplished by a hydraulic shock without any use of chemicals.

INTRODUCTION

In view of steadily increasing prices for high performance metal alloys, polymers are becoming a serious alternative construction material in apparatus design for niche applications. In the past polymeric heat exchangers had been developed to condensate corrosive media (Bigg et al., 1989; Reay, 1988), designed as bundled tubes and later as compact or foil heat exchangers (Zaheed and Jachuck, 2004; Cevallos et al. 2012). A novel PFHX concept became also feasible due to new material developments of PEEK (polyetheretherketone), which offers improved mechanical properties (Christmann et al., 2012).

The application of thin polymer films as heat transfer surface is a promising concept for industrial use. Christmann et al. (2013) described the apparatus concept of such a polymer film heat exchanger with its thermal and mechanical limits. As to that, further investigations on parameters influencing mineral scale deposition on polymeric heat transfer surfaces are required.

The scope of the presented work is directed to scaling effects under multi-effect-distillation (MED) conditions occurring in thermal desalination plants. In that respect the fouling affinity of different minerals is discussed, as well as strategies for mitigation and cleaning of deposits. In detail it concentrates on the comparison of stainless steel (1.4571) as a benchmark in apparatus design and the commercially available thermoplastic polymers polyetheretherketone (PEEK) and its modifications (Victrex Europa GmbH) as

well as polysulfone (PSU, Dr. D. Müller GmbH). Studied model salts are supersaturated calcium sulfate and calcium carbonate solutions.

POLYMER FILM HEAT EXCHANGERS

Material requirements in heat exchanger design depend on the application but address thermal, mechanical and chemical properties. Polymeric materials feature a high corrosive stability, but usually have very low thermal conductivities. The application of Nusselt correlations for falling film heat transfer on vertical planes illustrates the impact of thermal resistance of heat conduction on the overall heat transfer coefficient *U*. The non-dimensional Reynolds, Prandtl and Nusselt numbers are necessary to describe the heat transfer of condensation and evaporation side and are defined as follows (VDI, 2006; Schnabel and Schlünder, 1980):

$$Re = \frac{\Gamma}{\eta_L} \tag{1}$$

$$Pr = \frac{\eta_L \cdot c_{p,L}}{k_L} \tag{2}$$

$$Nu = \frac{h}{k_L} \left(\frac{v_L^2}{g}\right)^{1/3}$$
(3)

According to Nusselt (Nusselt, 1916) for laminar film condensation and neglect of vapor shear stress the following correlation for condensation holds (VDI, 2006):

$$Nu_{cond} = 0.925 \cdot \left(\frac{1 - \frac{\rho_G}{\rho_L}}{Re}\right)^{1/3}$$
(4)

The equations for film heat transfer at evaporating conditions are then (Schnabel and Schlünder, 1980):

$$Nu_{evap} = \sqrt{Nu_{evap, lam}^2 + Nu_{evap, turb}^2}$$
(5)

$$Nu_{evan \, lam} = 0.9 \cdot Re^{-l/3} \tag{6}$$

$$Nu_{evan,turb} = 0.00622 \cdot Re^{0.4} \cdot Pr^{0.65}$$
(7)

With eqs. (1) to (7) and a term for heat conduction (*s/k*) Fig. 1 gives the influence of both thermal conductivity *k* and wall thickness *s* on the overall heat transfer coefficient (see eq. (8)) at typical MED conditions ($T_{FF,in} = 70$ °C, $\Gamma_{FF,in} = 0.4$ kg·m⁻¹·s⁻¹ and $\Delta T = 5$ °C).

$$U = \left(\frac{1}{h_{cond}} + \frac{s}{k} + \frac{1}{h_{evap}}\right)^{-1}$$
(8)



Fig. 1 Thermal performance as a function of wall thickness and thermal conductivity

The high overall heat transfer coefficient of the turbulent film evaporation is drastically reduced when the resistance of heat conduction dominates the overall mechanism. This happens for a wall thickness of about 1 mm for stainless steel (k-value about 15 $W \cdot m^{-1} \cdot K^{-1}$) and 2 mm for Cu/Ni (k = 52 W·m⁻¹·K⁻¹), which are common wall thicknesses in industrial plate heat exchangers. The thermal conductivity of polymer materials, like (non-modified) PEEK, is in the range of $k = 0.25 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. According to Fig. 1 the maximum film thickness for most of the polymers should not exceed 25 µm for an efficient heat transfer process without extensive need of heat transfer area compared to standard materials. Christmann et al. (2012) reported on the application of 25 µm thin PEEK films as heat transfer surfaces at MED conditions of moderate thermal (T < 80 °C) and mechanical stress (pressure difference between condensation and evaporation side $\Delta p <$ 80 mbar). The buckling of the thin polymer films due to the pressure difference is reduced by applying a spacer geometry to lead the mechanical stress to the heat exchanger housing (see Fig. 2).



Fig. 2 Polymer film heat transfer surface supported by a point welded grid ($30 \times 30 \text{ mm}$).

The spacer grid also influences the local turbulence of the falling film, which enhances the overall heat transfer coefficient under this special process conditions (e.g. 3765 $W \cdot m^{-2} \cdot K^{-1}$ at falling film evaporation) reported by Christmann et al. (2013). Here the correlations for a plane surface (eqs. (5) to (7)) are not applicable, therefore Christmann et al. (2013) developed a new set of Nusselt correlations for the PFHX based on experimental results.

According to safety issues, a higher wall thickness as 25 µm is possible without heat transfer loss when using composite materials, that feature higher thermal conductivities (see also dotted line in Fig. 1 e.g. k = 1 W·m⁻¹·K⁻¹). Polymer films with mineral fillers (e.g. 30 % talcum) are commercially available and are an attractive alternative due to its improved mechanical properties. The PEEK film Aptiv[®] 1103 by Victrex Europa GmbH is an example for novel polymer film developments (k = 0.64 W·m⁻¹·K⁻¹). Besides its improved thermal conductivity, it is of more brittle behavior, which results in a higher Young's modulus compared to the Aptiv[®] 1000 polymer (Dreiser and Bart, 2012).

Besides pilot plant experiments for heat transfer studies, lab scale fouling experiments were carried out to quantify the technical performance of the PFHX concept. The results are in accordance to previous observations obtained from screening experiments reported by Dreiser et al. (2013). Fig. 3 shows the schematic flow sheet of the lab scale test unit. Plane surfaces as well as polymer filmspacer combinations can be tested (heat transfer area A = 0.052 m^2). The test section can be operated at falling film Reynolds numbers between Re = 100 and 1300. To prevent initial flow maldistribution the falling film feed of 0.2 m width is equipped with an inlet weir. The pressure of the left hand side (hot side) can be adjusted at a small difference (PIC) to the cold side (right hand side) to model the polymer film buckling also occurring in the pilot test section. The independent temperature control on the two different sides allows a mass and energy balance at various process conditions (flow rate, pressure and temperature differences).



Fig. 3 Schematic flow sheet of a lab scale PFHX.

RESULTS AND DISCUSSION

Fouling Prevention

Different promising polymeric materials for the PFHX concept have already been studied in respect to their fouling affinity in a screening device described by Dreiser et al. (2013). Fig. 4 presents the transient overall heat transfer loss due to gypsum scaling on different polymeric surfaces compared to a stainless steel surface at turbulent flow conditions (stirred vessel Reynolds number is 20 000).

It should be mentioned, that the thermal conductivities of the test materials given by suppliers and literature may differ. For that reason heat transfer coefficients are adjusted between 1.3 to 1.6 kW \cdot m⁻²·K⁻¹ for the polymeric materials and 2.2 kW \cdot m⁻²·K⁻¹ for the stainless steel surface when ensuring the same initial wall temperatures for all different test materials.

The overall heat transfer coefficient of the scaled stainless steel surface (1.4571) is markedly reduced to 53 % of its initial value within 68 hours. The relative heat transfer loss for the polymeric surfaces, however, under same conditions is smaller than 12 %. The scaling deposit of 324 g per m² stainless steel heat transfer area is about 11 times higher compared for example to polysulfone. The expected heat transfer loss during operation necessitates a larger heat transfer area, otherwise lower heat transfer losses result in a significant economic advantage. In addition to that, the lower mass of deposit also simplifies the PFHX cleaning.

In addition to CaSO₄, an investigation of CaCO₃deposition was carried out, since this salt is one of the dominating species in desalination scaling (Wildebrand et al., 2007). The temperature in different stages of MED desalination plants varies (50 °C < T_w < 70 °C) as well as the concentration due to evaporating water from the salt solution. Fig. 5 quantifies the effect of the initial wall temperature on deposition. The fouling Biot number ($Bi_f = U_0 \cdot R_f^*$) allows an independent quantification of fouling.

Higher local supersaturation due to higher wall temperatures enhances the process of deposition. For $T_{w,t=0}$ = 70 °C the resulting heat transfer loss is about 20 % after 67 hours and also the mass of the deposit changes by a factor larger than 4 in the range of studied wall temperatures (50 to 70 °C). Compared to conventional plate heat exchangers the fouling Biot numbers are quite moderate for this high $CaCO_3$ supersaturation. For e.g. hard water the fouling Biot number of a plate heat exchanger is $Bi_f = 0.31$ (VDI, 2006).

In a MED process the concentration of the brine changes in every stage and process conditions (T_{w} , c_{θ}) have a strong impact on save operation and economics. A reconsideration of the pressure and temperature in each stage can help to prevent scaling in first place. Table 1 shows the quantitative impact of different CaCO₃-concentrations on scaling after 67 hours. However, the impact on overall process efficiency can only be quantified by the discussion of heat exchanger cleaning.



Fig. 4 Overall heat transfer loss at different materials due to gypsum scaling.



Fig. 5 Fouling Biot number of CaCO₃-deposition on polymer heat transfer surface as a function of the initial wall

temperature ($c_0 = 4 \text{ mmol} \cdot l^{-1}$, $T_b = 40 \text{ °C}$, t = 67 h, stirred vessel Re = 20 000).

Table 1. Impact of concentration on CaCO₃-scaling on PEEK Aptiv[®] polymer ($T_{w,t=0} = 60$ °C, $T_b = 40$ °C).

$c_0,$ mmol·l ⁻¹	m_d , g·m ⁻²	$U_{f}/U_{0},$
3.0	2.9	0.98
3.5	7.2	0.94
4.0	24.6	0.89

Cleaning Strategy

The adhesive forces of most mineral scale deposits are very low on the studied polymer surfaces. Table 2 gives the surface free energy of the studied polymer films γ_{SG} and the interfacial energy difference of a CaSO₄-deposit layer and the polymer surfaces $\Delta \gamma_{CS}$. The surface free energy of the scaling deposit γ_{CG} was taken from Förster et al. (1999). Fouling kinetics and quantity of deposit is increased with lower interfacial energy difference due to better scale adhesion (Dreiser et al., 2013). Polymer surfaces with a high interfacial energy difference to the deposited species give evidence for an easy and fast in place cleaning strategy.

Table 2. Interfacial properties of different polymer surfaces.

surface	γ_{SG} ,	$\Delta \gamma_{cs}$,
	$mN \cdot m^{-1}$	mN·m ⁻¹
PEEK Aptiv [®] 1000	33.2	14.7
PEEK Aptiv [®] 2000	30.4	17.5
PEEK Aptiv [®] 1103	40.6	7.2
PSU	37.8	10.1

Since maintenance costs are the major foulingrelated cost factor in industrial heat exchanger operation (Steinhagen et al., 1993), a fast and efficient cleaning strategy is aspired. The special advantage of the present apparatus concept is given by the intrinsic flexibility of the thin polymer films. Due to the pressure difference between condensation and falling film evaporation side a buckling of the polymer film under operating conditions is evident (see Fig. 6). The deposit layer grows on the buckled surface during operation. Once the heat transfer loss due to fouling has reached a critical threshold an apparatus cleaning should be executed. By applying a pressure pulse between condensation and evaporation side, the polymer film moves and relaxes from buckling (Fig. 6). The rigid deposit layer is displaced and washed off by the falling film. A concept of solid matter discharge should be considered in the final heat exchanger design (e.g. screw-conveyor).

The process of displacement can be enhanced by a temporary increase of the falling film flow rate in order to apply a higher shear force acting to the deposit. To increase the stiffness of the scaling layer a drying or sweating can be performed prior displacement by stopping the falling film flow rate to ensure the evaporation of crystal moisture. Schematic profiles of pressure differences and falling film liquid load in such a cleaning procedure are presented in Fig. 7.



Fig. 6 Comparison of operation and cleaning of a PFHX.



Fig. 7 Operational cleaning procedure for deposit removal in a PFHX.

A whole cleaning procedure can be carried out in an interval of a few minutes. It should be mentioned, that after a first use of the foil the induction periods prior scaling are reduced due to nucleates left on the heat transfer surface (Christmann, 2011).

Fig. 8 represents the effect of such a cleaning procedure carried out in the lab scale PFHX unit (Fig. 3) at rivulet flow heating conditions. This flow regime enhances the deposition of scale due to dry patches resulting from film breakup (local supersaturation at interface). The relative wetted area of the surface ω is about 40 %.

The interval of repetition of this cleaning procedure depends on the critical overall heat transfer value acceptable for an efficient operation. This also depends on the operating conditions in each stage, like falling film liquid load (shear force effect on deposition), surface temperature (local supersaturation) and mineral concentration.



Fig. 8 CaSO₄-scaling at rivulet flow regime ($\Gamma_{FF,in} = 0.09$ kg·m⁻¹·s⁻¹ and $\omega \approx 0.4$) and deposit removal.

Fig. 9 shows the relation between heat transfer performance and the non-dimensional fouling extent. Theoretical values are calculated for MED process conditions using Nusselt correlations for film condensation and falling film evaporation (eqs. (1) to (8) as described above plus a variation of thermal fouling resistance). Experimental values are given for an experimental time of 68 h (see also Fig. 4).

With knowledge of acceptable industrial heat transfer losses during a process (e.g. 10 %) the cleaning interval can be estimated from experimental data. Within 68 hours (experimental time) the relative heat transfer loss due to CaSO₄-scaling does not exceed 12 % for all the studied polymeric surfaces. In comparison, the stainless steel surface (1.4571) had a loss of about 10 % of its initial heat transfer performance within 8.2 h. The benefit of polymeric heat transfer surfaces in that illustrative case appears on the one hand in an extension of the operational time (about factor 8 to 10 dependent on surface) until cleaning needs to be executed and on the other hand in an improved overall heat transfer coefficient (less scaling) during the whole operation.

The optimization of such cleaning intervals is then apparatus specific for an overall process like multi-effectdistillation or other heat exchanger trains. However, the detailed knowledge of scaling behavior based on single stage conditions (temperature and concentration) gives a basis to improve the efficiency of the overall process respectively helps in debottlenecking heat exchanger cleaning strategies.



Fig. 9 Relative heat transfer loss as a function of fouling Biot number, experimental values (CaSO₄-scaling, t = 68 h, from Fig. 4).

CONCLUSIONS

The operational features and challenges of PFHX can be concluded as follows.

- 1. The application of thin polymer films as heat transfer surface leads to high overall heat transfer coefficients comparable to standard materials (stainless steel, etc.).
- Compared to stainless steel the heat transfer loss due to scaling is very low on polymeric surfaces due to a very slow scaling kinetics and also the deposited mass of minerals is considerably smaller.
- 3. The low adhesion of the deposits (interfacial energetic effects) simplifies the cleaning in place and allows longer undisturbed operation.
- 4. The mechanical flexibility of the foils allows a cleaning in place without use of chemicals.
- 5. The cleaning procedure consists of a sweat period followed by a pressure pulse (rippling of the foil) and a final wash down of of the deposit.
- 6. The choice of the process conditions (pressure and temperature) significantly impacts the scaling quantity. Higher temperatures enhance deposition as well as higher concentrations. Basic results from single stage scaling give the basis for an optimization of multi-stage plants.
- 7. Experimental validation of the results observed for single model salts is required for a complex mixture likewise seawater.

ACKNOWLEDGEMENTS

The authors would like to thank the German Federal Ministry of Economics and Technology (BMWi) for the financial as well as the German Federation of Industrial Research Associations (AiF) for the administrative support of the project (IGF-16959N). The authors are also thankful to Victrex Europa GmbH for providing PEEK samples.

NOMENCLATURE

- A heat transfer surface, m^2
- Bi Biot number, -
- c_0 initial bulk concentration, mol·l⁻¹
- c_p specific isobar heat capacity, J·kg⁻¹·K⁻¹
- g gravitational acceleration, $m \cdot s^{-2}$
- *h* heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
- k thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
- *Nu* Nusselt number, -
- *p* pressure, mbar
- Pr Prandtl number, -
- *s* wall thickness, μm
- t time, h
- T_b bulk temperature, °C
- ΔT temperature difference cond/evap, °C
- $T_{FF,in}$ inlet temperature of falling film, °C
- $T_{w,t=0}$ initial wall temperature, °C
- U overall heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
- *Re* Reynolds number, -
- $R_{f_{1}}$ fouling resistance, m² K W⁻¹
- R_f^* asymptotic fouling resistance, m²·K·W⁻¹

Greek letters

$\Delta \gamma_{ij}$	interfacial energy difference between the phases i
	and j, mN·m ⁻¹
γ _{ij}	interfacial energy between the phases i and j, $mN \cdot m^{-1}$
Г	liquid load of falling film, kg·m ⁻¹ ·s ⁻¹
η	dynamic viscosity, kg m ⁻¹ s ⁻¹
	1 in a state with a size of 1 $m^2 a^{-1}$

- v kinematic viscosity, m² s
- ρ density, kg·m⁻³
- ω relative wetted area of heat transfer surface, -

Subscript

0	initial value
С	crystal phase
cond	condensation side
evap	evaporation side
f	fouled surface
FF	falling film
G	gas phase
in	inlet
L	liquid phase
lam	laminar flow
S	solid phase
turb	turbulent flow

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