COATINGS TO REDUCE FOULING IN PLATE HEAT EXCHANGERS: TWO CASE STUDIES

Olga Santos[1], Yves Adriaenssens[2], Clemens Wictor[3], Magnus Nilsson[3]

[1]Materials Technology and Chemistry, Alfa Laval Lund AB, PO Box 74, SE-221 00 Lund, Sweden.
Tel. +4646366074, e-mail: olga.santos@alfalaval.com
[2] Chemours Belgium BVBA, Antoon Spinoystraat 6A, 2800 Mechelen, Belgium.
[3]Gasketed Plate Heat Exchangers – Technology Development, Alfa Laval Lund AB, PO Box 74, SE-221 00 Lund, Sweden.

ABSTRACT

Fouling of heat exchangers in the chemical industry, oil & gas industry, district heating, power plants, among others, results in a loss of performance which leads to production stops for cleaning and therefore increased operation costs. One approach to mitigate fouling is to alter the properties of the metal surface. A coating to be successful in any plate heat exchanger application needs to have a good adhesion to the metal but also keep the heat transfer through the metal plates as unaltered as possible. This requires a thin coating with a relatively good thermal conductivity. The plates in a plate heat exchanger are subjected to plate-to-plate contact point wear when in operation which also puts an extra requirement for the coating. To be suitable, the coating needs to have a good mechanical stability to resist this plate-to-plate wear. Alfa Laval has a long experience in coating plates for diverse applications and in this paper two case studies will be presented. One in the paper industry and the other in the biofuel industry. A new type of multilayer Teflon™ coating from Chemours was used, specifically designed to show excellent fouling release properties along with limited thicknesses (30-50 microns).

INTRODUCTION

Fouling of heat exchangers occurs in a variety of different industries. It is very detrimental to the heat exchanger performance since it leads to a loss of its thermal duty and an increase of its pressure drop. At some point the heat exchanger will need to be taken out of operation for cleaning. This will lead to production losses and increased operation costs [1].

Biodiesel is increasing acceptance in the market as a fuel. Vegetable oils are currently the major sources for making biodiesel. Fouling in the biofuel industry consists of decomposition of hydrocarbons formed at high temperatures and polymerization of hydrocarbons into larger molecular components [2].

Scaling is the unwanted precipitation of crystals formed in a flowing medium as well as the direct crystallization at the solid surface. In the pulp and paper industry the most common form of scale is calcium oxalate, even if calcium carbonate and barium sulphate can also be present [3]. Calcium comes from water and the wood material [4] and oxalic acid is naturally present in wood and is also formed in the cooking and bleaching process of paper making [5]. Calcium carbonate salts have an inverted temperature solubility meaning that they will precipitate above a certain temperature (around 60°C), while calcium oxalate is a normal solubility salt, precipitating at lower temperatures [4, 6]. Other factors like pH, water hardness, flow rate, pressure, etc. will also influence the crystallization process. Calcium oxalate / carbonate scaling will lead to an increased pressure drop and a reduced heat transfer due to the hard insulating layer that builds-up at the metal surface (calcium carbonate thermal conductivity of 2,9 W m^{-1} k^{-1} [7]). In extreme cases the fouling layer will be so thick that the result is a clogged heat exchanger impossible to flush with an acidic cleaning in place (CIP). There are several approaches to mitigate scaling, like promoting turbulence (increasing the shear stress) and the use of chemical or physical additives that interfere with the crystal formation [8, 9, 10, 5]. Even though these strategies may reduce scaling they do not eliminate scale formation and will need to be complemented by chemical and mechanical cleaning. Alfa Laval's approach was again the use of coatings in order to decrease crystal adhesion to the stainless steel. Alfa Laval has had some successes in reducing fouling in heat exchangers by the use of coatings and some of the results will be presented in this paper.

Several authors have reported the use of coatings for the mitigation of crystallization and organic fouling [11, 12, 13, 14, 15, 16]. Höft et. al (2020) [14] investigated the use of several fouling resistant coatings (DLC, SICON, SICAN, F-DLC and SiO_2) applied in a heat exchanger in contact with biogas. The found that the SiO_2 coating showed the best results in minimizing particulate fouling. Oldani et. al (2016) [15] studied the ability of perfluopolymers coatings applied on heat exchangers to reduce fouling. After a 5 month operation they observed a 56% decrease of heat transfer for the coated compared to 62% for the uncoated, and a three times higher increase in heat transfer resistance for the uncoated. A Ni-P-PTFE nano composite coating applied on corrugated plate heat exchangers in order to minimize fouling was seen to decrease the amount of fouling and improve the cleanability [16]. While some improvements in fouling and cleaning were observed for some of the coatings, there is only, to the author's knowledge, the Alfa Laval commercially available coated plate

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heat exchanger for crude oil cooling application. This is due to the complexity of both the fouling mechanism and the coating properties. Besides being able to reduce foulant adhesion a coating, to be suitable to use in a heat exchanger, needs to have a decent thermal conductivity, good wear and abrasion resistance, good temperature and chemical resistance and a good adhesion to the metal substrate. Another aspect one needs to consider regarding coatings for heat exchangers is the influence the coating will have on the thermal performance of the PHE (Plate Heat Exchanger). The coating will act as a fouling layer in respect to the heat transfer, however due to the low thickness and reasonable thermal conductivity (~ 2 W / m K) of the used coatings the reduction in heat transfer will be minimal. It should also be noted that an uncoated heat exchanger with a thick deposit (low heat conductivity) will result in a lower thermal performance as compared to a coated heat exchanger where only a thin fouling layer deposits.

In the following sections the results from two field tests performed at Alfa Laval customers will be presented.

EXPERIMENTAL

Surface treatment

For the Chemours coatings, stainless steel heat exchanger plates from Alfa Laval were grit blasted using aluminum oxide (p80, 3 bar) to achieve surface roughnesses R_a of 2-3 µm. 2-layer FEP and 3-layer PFA combinations were sprayed using robotic application with precise coating thickness control. Processing has been done with specific drying cycles in between the layers and a final cure of 380°C/340°C. The 2-layered FEP combination consisted of solvent-based NMP-free primer 700G-104 and FEP topcoat 700G-300. The 3-layered PFA combination consisted of solvent-based NMP-free primer 700G-104, water-based 700G-204 midcoat and water-based 700G-400 PFA topcoat. Both topcoats were developed for maximum smoothness and foul & release properties. Both Teflon™ coating systems are food-contact compliant in Europe.

Coating properties

Water contact angles were measured by the static sessile drop method, using a mobile drop goniometer from Kruss. Contact angles were measured on coated planar 2B steel test samples, as the geometry of the HE plates did not allow for precise direct measurements. The coating thickness was measured using a coating thickness gauge model *Dualscope*® FMP100 according to ISO 23620:2003 with sampling at 30 places on the coated sample. The Average Surface Roughness (R_a) was measured on the coated samples with a Perthometer M4P from Perth. Three measurements were made on sample. The accuracy of the instrument is ±10%.

The water contact angle, coating thickness and surface roughness are presented in Table 1.

Table 1. Water contact angle (ϴ) and coating thickness (µm) on the uncoated and coated plates.

Coating	Θ_{water} (°)	Thickness (µm)	Roughness (µm)
Uncoated	66 ± 6	---	0.2 ± 0.02
2K-FEP	99 ± 1	31 ± 3	0.1 ± 0.01
3K- PFA	102 ± 1	41 ± 3	0.2 ± 0.01
Coating 1	100 ± 1	10 ± 1	0.04 ± 0.002
Coating 2	110 ± 2	30 ± 5	0.3 ± 0.02

Experimental set-up

Scaling application

A field test was performed with coated wide gap PHE plates installed at a pulp & paper industry. The coatings were: 2-layer FEP and 3-layers PFA from Chemours. The test consisted of two WG350 plate heat exchangers (HE1 and HE2) with 5 coated 316SS, 0.8 mm plates in each unit. The plates were coated on both sides. The run time was 2 weeks. The coated plates were inspected by the naked eye and the coating condition tested with a permanent marker.

Duty PHE (HE1):
S1 -> T1: Process water 85°C => 50°C
T4 -> S4: Water 45°C => 80°C
Number of plates: 360

Duty PHE (HE2):
S1 -> T2: Process water 50°C => 34°C
T3 -> S4: Water 25°C => 45°C
Number of plates: 126

A second test was performed with a fully coated PHE (HE1). The duration of the test was 1 year.

Biofuel application

A field test was performed with coated M15 PHE plates installed in a biofuel plant. The coatings were: coating 1 (25 plates), 2-layers FEP (5 plates), 3-layers PFA from Chemours (5 plates) and coating 2 (25 plates).

The duty is highly fouling where the PHE fouls after 1-2 weeks and is opened every 12 weeks. The test consisted of a M15B plate heat exchanger with 60 coated 316SS, 0.5 mm plates. The plates were coated on both sides. The running time of 12 weeks. The coated plates were inspected at site and after inspection the PHE was reassembled and run for yet

12 more weeks. The entire plate pack was then sent to the R&D Alfa Laval lab in Lund for evaluation after a total of 24 weeks running time.

Duty:
S1 -> S2: Refined vegetable oil 100°C => 55.7°C
S3 -> S4: 90% vegetable oil 20°C => 70°C

RESULTS

In the following sections the results of both field tests, scaling on a pulp and paper industry and fouling on a biofuel plant, will be presented.

Scaling application

One of the WG350 PHE (HE1) installed at the paper industry can be seen in Fig. 1. The HE2 had already been opened (on the day before the inspection) and the coated plates were set aside for inspection (Fig. 2). Of the 5 installed coated plates, 2 were coated with the 3-layers PFA and 3 with the 2-layers FEP coating (darker green). The temperature of the process side on this HE goes from 50°C to 34°C and therefore the scaling in less problematic compared to the HE1. The coated plates were placed at the back (20 plates from the pressure plate) of the plate pack. It was seen that the coated plates were covered with fouling which consists of calcium oxalate and fibers (Figs. 3 and 4).

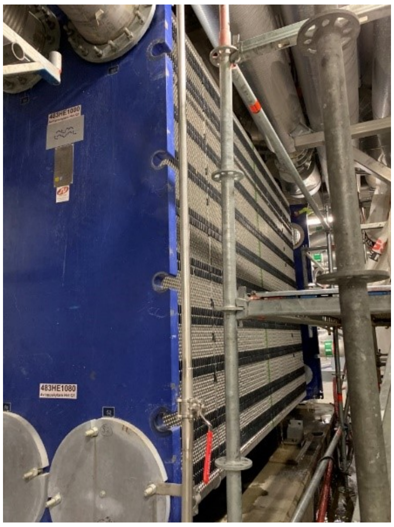

Fig. 1 - The WG350 GPHE (HE1080) with the coated plates at the customer site.

The scaling adhered loosely on all coated plates and was displaced with no force required (Fig. 5). On the 2-layer coated plates one can see that a big part of the scaling from one plate was collected on the adjacent plate when these were separated (Fig. 6). The plates were partially cleaned with high water pressure jet and the scaling is easily removed from the plates (Fig. 7). No delamination was seen on the coated plates but some small blisters were present on the 3-layer coated plates (Fig. 8). This was seen all over the plate (no dependency on the temperature). On the 2-layer coating these small blisters were seen only on limited areas of the plate (Fig. 9). All coated plates still showed repellency and easy to clean effect all over the plate (Fig. 10).

Fig. 2 - Coated plates taken out from the unit HE1082.

Fig. 3 - Fouling on the 3-layer coating (left) and 2-layer coating (right).

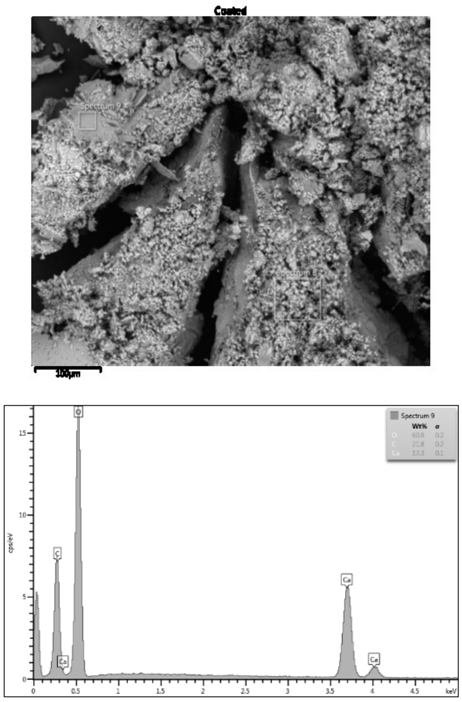

Fig. 4 – Representative spectrum of the deposit collected from a coated plate.

Fig. 5 - Low adhesion of the fouling to the plate. It can be removed easily with the finger.

Fig. 6 - The fouling layer from one coated plate was collected on the adjacent coated plate when the plates were separated.

Fig. 7 - Coated plate that was partly cleaned with high water pressure jet. The fouling layer was removed very easily.

The other PHE (HE1) was open on the inspection day. On this HE the process water goes from 85°C to 50°C and the plates foul more. The 5 coated plates (2 plate with 2-layer coating and 3 plates with 3-layer coating) were installed in the middle of the HE. The amount of fouling on the uncoated plates was substantial consisting of a very thick layer of soft material (Fig. 11). The calcium oxalate scale builds up on the plates creating a rough surface where the flowing fibers can easily attach. The amount of fibers in the process water is 50 ppm according to the customer. On the coated plates almost no fouling was present (Figs. 12 and 13). The difference in amount of fouling between uncoated and coated plates was tremendous as can be seen on previous figures and on Fig. 14 where the channel was formed by an uncoated and coated plate.

Fig. 8 – Blisters on the 3-layer coating.

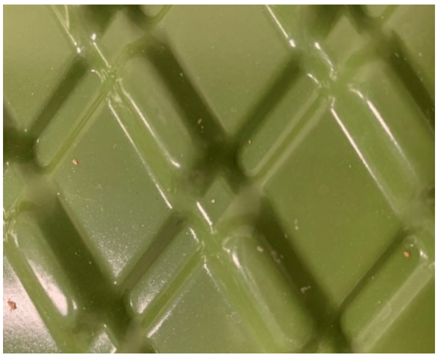

Fig. 9 – Some blisters on the 2-layer coating.

Fig. 10 – Repellency on the 3 and 2-layer coatings after the field test.

The coated plates that were in operation for 1 year are shown in Figs. 15 and 16 from both sides of the plate. It is seen that minor fouling was present on the 3-layer coating (Fig. 15) while on the 2-layer coating the amount of fouling was more extensive (Fig. 16) and the deposit was also more difficult to remove with a wet cloth. The only coating damages seen were wear at the contact points on the product

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side. This was seen for both coatings (Figs. 17 and 18). To assess the coating condition a pen marker test was performed. The 3-layer coating kept some of its repellency and easy to clean effect as seen by the beading effect of the marker ink (Fig. 19) and the total removal of the ink with a dry tissue. On the other hand, the 2-layer coating showed no repellency on the process water side (Fig. 19) and a decrease in the easy clean effect.

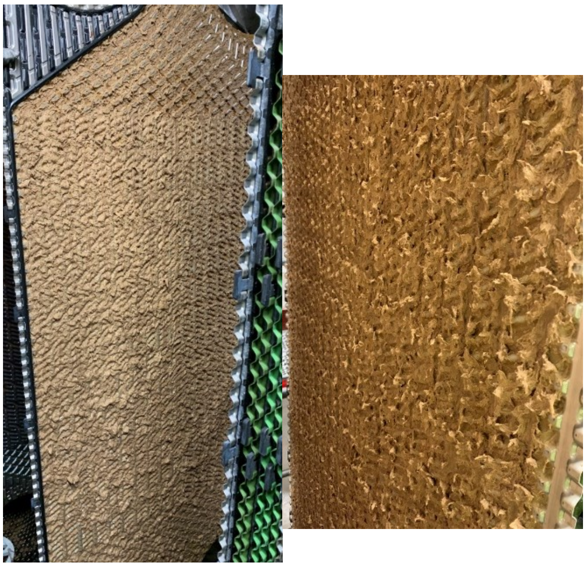

Fig. 11 – Fouling on an uncoated channel.

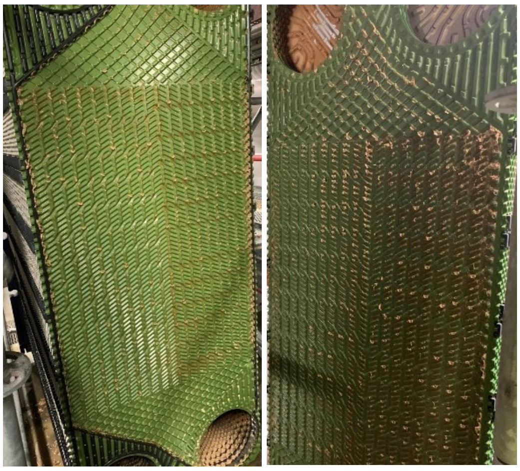

Fig. 12 – Fouling on the 2-layer coated channel.

Biofuel application

The fouling appearance on an uncoated plate is shown in Fig. 18 (picture provided by the customer). Evaluation of the coatings was performed at the R&D Alfa Laval in Lund. The coated plates have been in operation for a total of 24 weeks. The plates coated with coating 1 were found to be covered with fouling (Fig. 19). The fouling adhered strongly to the plate and it was not possible to clean with a tissue. The pen test showed no repellency and no easy to clean effect (Fig. 20). On the plates coated with coating 2 less fouling was seen compared to the uncoated (compare Fig. 18 with 21) and the adhesion of the fouling was also lower on this coating. The pen test showed no repellency but easy to clean effect (Fig. 22). The lowest amount of fouling was seen on the Chemours coated plates (Figs. 23 and 24). The 3-layer coating had a slightly lower amount of fouling compared to the 2-layer coating. The adhesion of the fouling on both coatings was also low making it easy to remove the deposit with a tissue. The pen test showed both repellency and easy to clean effect (Fig. 25).

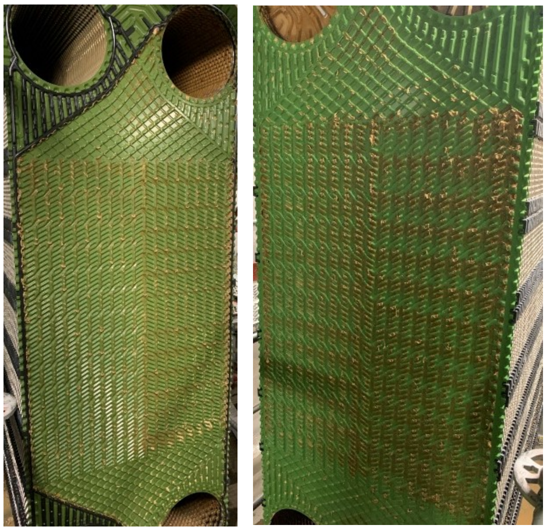

Fig. 13 – Fouling on the 3-layer coated channel.

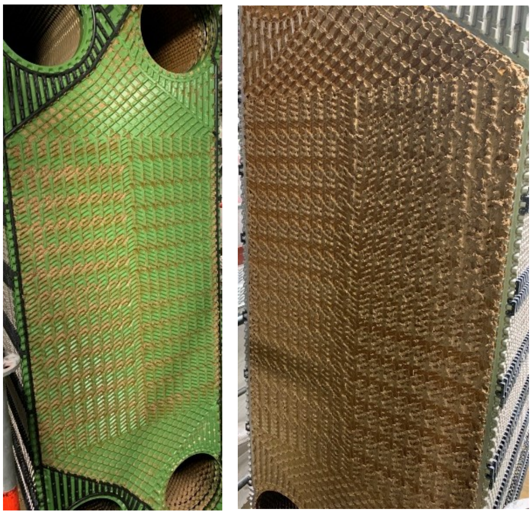

Fig. 14 – Fouling on a channel formed by a coated (3-layer) plate and an uncoated plate.

DISCUSSION

Fouling can be influenced by many parameters, such as media composition, surface temperature, operating conditions, and surface properties. It is generally accepted that scaling amount and strength is influenced by surface roughness [17]. A higher

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surface roughness leads to a larger amount and a higher strength of the scaling layer. This is explained by the increased surface area of the rougher surface and the change for the peaks to act as nucleation sites and for the valleys to act as a shield for the crystals against removal by the shear stress [18]. In addition, the induction time is also influenced by the surface roughness, where a higher roughness leads to a shorter induction time [19, 20].

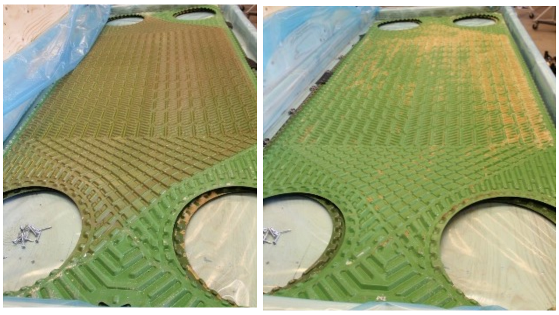

Fig. 15 – Fouling on the 3-layer coated plate. Water side (left) and process water side (right).

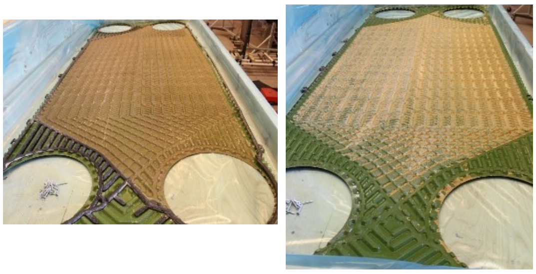

Fig. 15 – Fouling on the 2-layer coated plate. Water side (left) and process water side (right).

Fig. 16 – Wear at the plate-to-plate contact points on the 3- (left) and 2-layer coating (right).

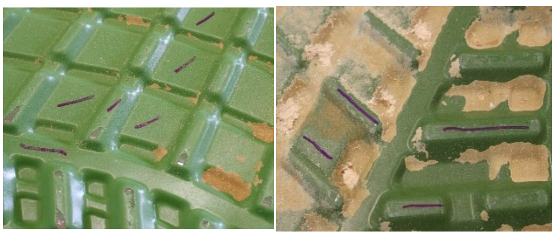

Fig. 17 – Little repellency on the 3-layer coating (left) and no repellency on the 2-layer coating (right).

In the present study the surface roughness was similar for both the steel and the polymeric coatings, FEP and PFA, so the decrease in scaling cannot be attribute to the roughness. The surface free energy is a direct measure of intermolecular forces that affect the attraction of the bulk liquid to the surface layer [21]. Several studies have also observed a lower crystal adhesion on the surfaces with the lower surface energy [22; 21]. Cheong et al. (2013) [22] observed higher scaling for stainless steel surfaces as compared to coated stainless steels having a higher water contact angle. However, there are also reports on lower scaling amounts on surfaces with low surface energies and even others where no correlation between scaling and surface energy was seen [23]. The PFA has a slightly higher contact angle meaning lower surface energy than FEP and it was the one who showed better anti-scaling properties, even if the roughness was also slightly higher. Obviously, the reduction of scaling on a certain solid surface cannot be attributed to only one surface property but is the combined effect of different surface properties. Dowling et. al (2010) [24] also observed a reduction in the adhesion of calcium carbonate slurry from a paper making industry to siloxane and fluorosiloxane coated surfaces after 15 days static conditions. The coatings were however not mechanically robust for application in plate heat exchangers due to their nm coating thickness. They attributed their findings to the low surface energy of the coatings as compared to the stainless steel metal.

From the different coatings tested at the biofuel plant, coating 2 and the Chemours coatings showed a good antifouling effect. Coating 2 has the highest contact angle but also the highest roughness while PFA has a higher contact angle compared to both stainless steel and the other coatings but the same or higher surface roughness. Both coatings showed however a reduction in fouling and improvement of cleanability as compared to the uncoated plate. The same was observed by Dowling et. al (2010) [24] who found a reduction of lube oil fouling after 30 days at 95°C on fluoropolymer and fluorosiloxane coatings applied on separator discs. They explained the results due to the lower surface energy of the coatings.

Fig. 18 – Fouling on the uncoated plate.

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Fig. 19 – Fouling on the plates with coating 1.

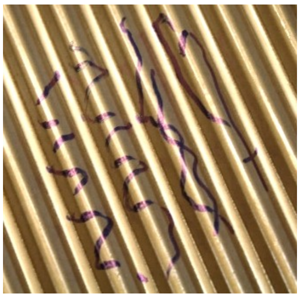

Fig. 20 – No repellency and no easy clean effect seen on the coating 1.

Fig. 21 - Fouling on the plates with coating 2 and the uncoated end plate.

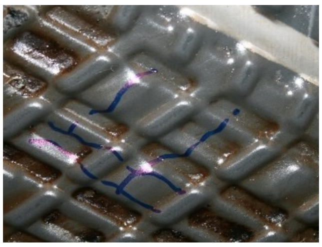

Fig. 22 – No repellency but easy to clean effect on the coating 2.

Fig. 23 – Fouling on the 2-layer coating.

Fig. 24 – Fouling on the 3-layer coating.

Fig. 25 – Repellency on the 2- and 3-layer coating.

CONCLUSION

Scaling application

The scaling layer on the coated plates was very loose and could be removed with no force, i.e., the adhesion of the scaling to the coated plates was minimal. Only small blisters and no delamination were seen on the coated plates. Both coatings showed repellency and easy to clean effect, after the 2 weeks run time. The coated plates installed on the unit HE1 showed a huge improvement in scaling reduction. In this HE almost no fouling was present

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on the coated plates while a very thick fouling layer was covering the entire surface of the uncoated plates.

After one year operation time no blisters or delamination was seen on neither of the coated plates. Both coated plates suffered from wear at the plate-to-plate contact points on the process water side. The 3-layer coating performed better in the present application, showing less scaling, lower scaling adhesion, better repellency and easy to clean properties.

Biofuel application

The plates coated with coating 1 showed the largest amount of fouling. On this coating the fouling was strongly adhered and no repellency or easy to clean effect was present. The plates coated with coating 2 showed a lower amount of fouling compared to the uncoated and the deposit was easily whipped off with a tissue. No repellency was seen but the easy to clean effect was still present. The Chemours coated plates showed the lowest amount of fouling. The 3-layer coating fouled slightly less than the 2-layer coating. No delamination was seen in neither of the coatings. Both coatings showed repellency and easy to clean effect, after the 24 weeks run time. The Chemours coating was found to be the most suitable for this application.

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