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EFFECT OF STRUCTURED SURFACES ON FOULING AND CLEANING BEHAVIOUR IN PLATE HEAT EXCHANGERS

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ABSTRACT

In plate heat exchangers a good heat transfer from the plate to the liquid falling film is crucial. Therefore, results have shown that structured surfaces can improve heat transfer significantly by changing the degree of turbulence. Nevertheless, the use of structured surfaces is not widespread because of concerns regarding hygiene. But since other publications could already show that results from heat transfer examinations can be transferred also to mass transfer in a similar way, it is assumed that structures might even have a positive effect on cleaning and therefore compensate influences regarding increased fouling. The cleaning tests were performed in a liquid falling film test rig with a polysaccharide model soil and deionised water as cleaning fluid. Three different structures were compared on Aluminium plates. It could be shown that the positive effects of surface structures regarding heat transfer overweigh the negative influence on hygiene.

INTRODUCTION

In plate heat exchangers thermal energy has to be transferred from one fluid to another through a metal plate. It is crucial to reach a good efficiency factor. When flat plates are used, the liquid film is mostly laminar. As a result, the temperature profile near to the plate has a low increase or decrease because mixing within the film is poor and the heat is only transferred slowly between the laminar layers. Studies have shown that heat transfer can be significantly increased with the use of structured plates, particularly by using dimples. The structures are changing the laminar flow into a more turbulent flow, so that the temperature profile near to the plate changes and heat can be transferred faster and more efficient. The laminar sub layer, which impedes the heat transfer, is reduced. Turnow et al. (2012) showed that the use of dimples can increase the heat transfer by 105 %, whereas the surface is only enlarged by 18 %. The authors determined several areas of turbulence in and around the dimples depending on the dimple geometry, which are shown in Fig. 1.



Fig. 1 Turbulence areas resulting from dimples: I) Primary vortex pair, II) Secondary vortices, III) Recirculation zone (Turnow et al., 2012).

Especially the vortex areas are helpful with respect to heat transfer because they support mixing and the reduction of the laminar sub layer. The studies revealed that the ratio between the depth and the diameter of the dimples has a major influence on the way these three areas are formed. It showed that a ratio of 0.26 leads to the best results regarding good heat transfer (Turnow et al., 2012). If it is lower, the vortices are not big enough for a good mixing. Is the ratio too high, the recirculation zone is becoming too big and the vortices are not able to generate a proper mixing process there.

Other studies, which are showing the positive influence of several surface structures, were published e.g. by Chung et al. (2013), Turnow et al. (2011), Liu et al. (2015), G. Xie et al. (2015), Y. Xie et al. (2015), Kornev et al. (2005) or Mahmood et al. (2002). One of the reasons why structured surfaces are still not used extensively is that there are concerns regarding hygiene. It is assumed that structured surfaces are tending to increased fouling and are therefore harder to clean, although there are no publications yet proving these assumptions. Within this paper work, the validity of these concerns is examined with the aim to see if it might be reasonable regarding hygiene to use structured surfaces in plate heat exchangers. Other publications, e.g. by Schöler (2011), could already show that some results from

heat transfer examinations can also be transferred to mass transfer which is relevant for cleaning. This suggests the assumption that surface structures, like dimples, might even have a positive effect on the cleaning behavior.

In a dip coating apparatus it was tested which influence structures like dimples have on the fouling behaviour. In a liquid falling film test rig cleaning tests were performed to see how the structures affect the cleaning behaviour in different areas of the plate. The tests were done with a food model soil which has a cohesive cleaning behaviour when it is removed with a liquid falling film. Different volumetric wetting rates in the range of $1.5 \text{ m}^3/(\text{h*m})$ to $2.5 \text{ m}^3/(\text{h*m})$ and three surface structures were examined.

EXPERIMENTAL TECHNIQUES AND METHODS

All cleaning tests have been performed with a gravity driven falling film. The test rig (Fig. 2) has already been described in previous publications (Fuchs et al., 2013 and 2014).



Fig. 2 Test rig for falling film.

A pump unit is transporting the fluid to a surge tank on top of the enclosure of the test rig. A flow meter can provide different flow rates to the spray lance (inner diameter: 16 mm, length: 100 mm; 12 equally spaced holes, diameter: 2 mm) which is laying the film on the inlet area (length 500 mm). Beneath this zone soiled sample plates can be placed in the measuring area (length 300 mm) where the film is formed with reproducible flow conditions and less influence of the fluid distribution device. The fluid temperature was held constantly at 25 °C \pm 1 °C by a heating device. The cleaning process is monitored by a camera system which detects the fluorescence of the soil induced by UV light.

Sample plates with different kinds of structures were produced for the experiments (Fig. 3). The plates (dimension 300 mm x 100 mm) were made of Aluminium (EN AW 2007) for reasons regarding lower costs, weight and production effort. The structures were produced with a ball cutter. Three different structures were tested within this work: two kinds of dimples according to the publications from Turnow et al. (2012) and Chung et al. (2014) and

horizontal grooves with a ratio of width and depth similar to the Turnow-dimples. As reference a flat test plate was used.



Fig. 3 Geometry of the structured test plates, a) Turnowdimples (Turnow et al., 2012), b) Chung-dimples (Chung et al., 2014), c) horizontal grooves.

Dip Coating Studies

The tests with regard to the influence of surface structures on the fouling behaviour were performed in a dip coating apparatus which was designed within this work (Fig. 4). The plates can be positioned in a clamp which is hanging on a rope. The clamp is held in its position by linear guides and can be moved up and down reproducibly by an engine. The movement speed can by varied by a pulse width modulator. Different soils can be filled into the tank, where the test plate is immersed in. For the tests, it was pulled up with a speed of 1.5 mm/s. Downwards it was dipped into the soil with a speed of 3 mm/s.



Fig. 4 Apparatus for defined dip coating.

The model soil consisted of 0.5 g Xanthan gum and 3 g zinc-sulphide crystals mixed with 1 L of deionized water. Xanthan gum is relevant in food and pharmaceutical industry and is used e.g. as thickener. The zinc-sulphide was used as luminescent tracer which is distributed homogeneously in the soil to make it visible for the camera system under UV light. It is a particulate component (mean

particle size 20 μ m \pm 3 μ m) what affects also the cleaning behaviour. But since also a lot of cosmetic and food products contain particulate components, the used model soil suspension covers a relevant number of real industrial deposits. The soiled plates were dried under defined conditions (23 °C, 50 % humidity) for 24 hours in a vertical position.

To analyse the fouling behaviour, the plates were weighed before and after the dip coating procedure. On this way, it was possible to determine the amount of soil remaining on the plates after the dip coating. In addition, the soiled plates were photographed under UV light to detect the local distribution in and around the structures on the surface.

Cleaning Studies

The cleaning tests were done in the test rig for liquid falling films, which was described before. The used cleaning fluid was deionized water and three different volumetric wetting rates were examined (1.5 m³/(h*m), 2.0 m³/(h*m), 2.5 m³/(h*m)). The plate angle was held constantly in a vertical position. At first, tests were done with the plates soiled by dip coating, to see if the expected increase of soil mass, due to the structures, can be compensated by better cleaning behaviour due to dimples and grooves. In a second step, the soil was applied with an automated two-fluid nozzle (soil + compressed air). On this way, plates are soiled very homogeneously and reproducibly so that cleaning results can be compared better. The aim was to coat the plates inside and outside of the structures with the same amount of soil, so that the influence of the different cleaning behaviour is eliminated. On this way, it was possible to monitor the local effects of the structures on the cleaning behaviour detachedly.

To analyse the cleaning behaviour, the cleaning procedure is monitored with a camera under UV light. The zinc-sulphide tracer makes the soil visible so it can be detected which areas are still soiled and which ones are already clean. Photos were taken every five seconds to guarantee that the cleaning process can be monitored temporally and spatially resolved.

To compare the several cleaning tests, the mean cleaning rate \overline{R}_{95} introduced by Mauermann et al. (2010) was used:

$$\bar{R}_{95} = (0.95 \cdot \bar{m}_0) / \bar{t}_{95}$$
 (1)

The cleaning rate \overline{R}_{95} represents the ratio between mass of the cleaned soil \overline{m}_0 and the time \overline{t}_{95} at which 95 % of the initial soil is removed. To determine this time, the photos were analysed by a program which detects all soiled and cleaned areas on the surface on the basis of the grey value which can be locally measured resulting from the fluorescence of the soil. A high cleaning rate represents a fast cleaning process and is an indicator for time efficient cleaning. The cleaning rate was determined with regard to the whole plate on the one hand and on the other hand also spatially resolved in dimples and grooves and between them.

RESULTS AND DISCUSSION

Fouling Behavior

To evaluate the fouling behaviour dependent on the surface structure, the test plates were weighed before and after the dip coating process so that soil mass can be determined. Since the structures are leading to different surface areas, the measured soil mass was considered in relation to the several area values to get comparable results which are shown in Fig. 5.



Fig. 5 Relative soil mass after dip coating dependent on the surface structure.

It indicates that the structured surfaces are tending to significantly higher fouling. The relative soil mass on the dimpled surfaces was around two times as high as it was on the flat plates. For the horizontal grooves it was even higher. The pictures taken of the soiled plates (Fig. 6) are showing that the soil accumulates at the sharp edges on the bottom of the dimples and grooves. Only if a certain amount of soil is reached there, it continues draining down the plate. Also above the structures, especially for the dimples, the soil accumulates on the upper sharp edges and flows around the structures so that these areas are soiled slightly more than others.



Fig. 6. Soiling behaviour for different structured surfaces.

Therefore, also dip coating tests with rounded edges have been done for the horizontal grooves. The edges have been smoothed manually to see if it is possible to improve the draining behaviour of the soil. The results are shown in Fig. 7. It reveals that the soil mass, remaining in the grooves, can be reduced significantly by removing the sharp edges so that it is easier for the soil to overcome them and drain down the plate. In addition, the soil is spread more homogeneously, also in the area between the grooves, probably because the soil film is tearing less.



Fig. 7. Dip coating comparison between grooves with sharp edges (left) and grooves with rounded edges (right).

Nevertheless, the dip coating procedure as well as the used soil are representing a worst case scenario. The fluids in heat exchangers have normally a far less viscosity than the Xanthan gum so that they are less vulnerable regarding sharp edges. Also the fluid in a heat exchanger is normally in a constant flow. Therefore, the fouling normally results from products which are slowly accumulating on the plates over time due to the high temperatures.

Cleaning Behavior

The first cleaning tests were performed with the test plates soiled by dip coating with Xanthan gum. The aim was to examine the cleaning behaviour of structured surfaces under realistic conditions (worst case). The tests were done at a volumetric wetting rate of 1.5 m³/(h*m) with deionized water. The cleaning process was analysed regarding cleaning time and cleaning rate. The cleaning time \bar{t}_{95} represents the time which is needed to clean 95 % of the surface. The cleaning rate \bar{R}_{95} is calculated from the relative soil mass \bar{m}_0 and the mean cleaning time like it is shown in Eq. (1).



Fig. 8. Cleaning time and cleaning rate depending on surface structures for dip coated plates.

The results in Fig. 8 are showing that the difference, which could be measured regarding cleaning time, is pretty low, although the amount of remaining soil on the structured surfaces was significantly higher than on the flat plate. With regard to the structured surfaces, Turnow-dimples are showing the best cleaning behaviour with an increase regarding cleaning time of only around 6 %. The cleaning time with the Chung-dimples is significantly higher. The horizontal groves needed around 25 % longer on average to get cleaned than the flat plate. These relatively small differences regarding cleaning time are finding expression in the cleaning rate. It indicates that the removed soil per minute is significantly higher on the structured surfaces than on the flat plate. To find an explanation for this effect, the pictures of the cleaning process were regarded in detail with respect to local differences in cleaning behaviour.



Fig. 9. Cleaning progress using the example of horizontal grooves.

Fig. 9 shows the cleaning progress exemplary on a plate with horizontal grooves. It can be seen that in the first 400 s nearly no soil removal is taking place because the Xanthan gum needs time to swell. After the swelling phase the removal increases rapidly. The images are showing that, although the grooves are soiled clearly more than the flat parts between them, the Xanthan gum there is removed faster. Even after the groves are completely cleaned, there is still soil remaining between them. It is possible that the enhanced turbulence inside the grooves is leading to this improved cleaning behaviour. Another explanation could also be that the thicker soil layer is providing a better target for the liquid falling film so that it is easier to remove the soil film adhesively instead of cohesively by diffusion.

The sharp edges on the structures could be another reason for the decreased cleaning rate between the grooves. It is possible that the liquid falling film is tossed out of the grooves on the sharp edges so that the local wetting rate behind them, directly on the plate, is reduced.

To compare the cleaning behaviour dependent on the different structures without the influence of the soil layer thickness, additional tests were performed with homogeneously soiled plates. The relative soil mass, produced with the automated two-fluid-nozzle, was on a constant level around 0.9 mg/cm² with a variation coefficient of 10 %. For these tests the volumetric wetting rate was varied (1.5 m³/(h*m), 2.0 m³/(h*m), 2.5 m³/(h*m)). The results from these tests (Fig. 10) do not approve the results which were determined within the tests with dip coated plates in all points. The differences in cleaning time are similar. For the flat plate and the Turnow-dimples it is nearly the same. Again, the Chung-dimples require the longest time to get cleaned. But since the soil mass does not vary between the different structures within these tests, the cleaning rate for the structured surfaces is worse this time.



Fig. 10. Cleaning time and cleaning rate depending on surface structures and wetting rate for homogeneously soiled plates.

The results also show that the influence of the volumetric wetting rate is different for the structured surfaces than it is for the flat plate. For the flat plate the cleaning rate increases slightly with a higher volumetric wetting rate as it was expected and as other studies have already proven (Fuchs et al. 2014). In contrast, for the Turnow-dimples and the horizontal grooves cleaning time and cleaning rate are nearly constant despite the increasing volumetric wetting rate. For the Chung-dimples the cleaning behaviour is becoming even worse. An explanation for these results might be that due to the higher volumetric wetting rates in combination with the sharp edges of the structures some areas inside and behind the structures cannot be reached with a sufficient local wetting rate, so that cleaning is impeded there.

Fig. 11 is showing the cleaning behaviour of a homogeneously soiled plate exemplary for the Turnowdimples. On the first pictures it looks like as if the dimples were soiled more, but this is only a result of light reflections in the dimples what make them look brighter than the flat surface. It was measured that the soil mass in the dimples is the same as it is on the flat surface. The images are showing that the soil is removed very evenly when Turnow-dimples are used. The finding, that dimples are cleaned faster than the flat surface, could not be approved within the tests with homogeneously soiled plates, neither for the Turnowdimples nor for the Chung-dimples.



Fig. 11. Cleaning behavior with homogeneously soiled plates exemplary for Turnow-dimples @ 2.0 m³/(h*m).



Fig. 12. Comparison of the local cleaning behaviour dependent on the surface structure.

Fig. 12 is showing the evenly cleaning behaviour for the flat plates and the Turnow-dimples. For the Chung-dimples it can be noticed that the bottom of the dimples is a critical area where cleaning is progressing slower than on the rest of the plate. This can be explained either with worse flow conditions on the bottom of the dimples or it might also be possible that the soil mass there is slightly higher than in the rest of the dimple because it accumulated there during the drying process. For the horizontal grooves the image is showing that the grooves are basically cleaned faster than the rest of the plate except for the part on the bottom of the grooves similar to the Chung-dimples. The area between the grooves needs more time to get cleaned. Possible reasons for that were already explained above with regard to the cleaning tests with dip coated plates. It is assumed that the sharp edges are one major reason for the poor cleaning behaviour in these areas. The fluid is probably lifted off from the surface due to the sharp edges and has therefore less cleaning effect on the soil there.

CONCLUSIONS

- 1. Structured surfaces can lead to significant worsening of the fouling behaviour on metal plates. Especially sharp edges are a major reason why soil is accumulating in certain areas and is not able to drain as well as on a flat plate.
- 2. The smoothing of edges can improve fouling behaviour although it is still worse than on flat plates. Nevertheless, the performed dip coating tests with Xanthan gum are representing a worst case fouling scenario. On real plate heat exchangers the product is normally less viscous and therefore less vulnerable for sharp edges. In addition, the constant flow of the product in heat exchangers leads to a less adherence propensity than it is in a dip coating process.
- 3. The cleaning tests also showed that for the Xanthan gum the higher soil mass on the structured plates is only leading to a minor increase of the cleaning time. The cleaning rate was even higher on the structured surfaces than on the flat plate.
- 4. The cleaning tests with homogeneously soiled plates could not approve this finding of a higher cleaning rate for structured surfaces. The cleaning time for structured plates was also slightly higher than it was for the flat sample plate although the relative soil mass was the same on all plates.
- 5. The cleaning tests also revealed several critical areas for some structures which are harder to clean than others. Especially the smoothing of the sharp edges seems promising to improve the cleaning behaviour.
- 6. In general, it can be determined that the negative effect of structured surfaces regarding fouling and cleaning (6 % increase of cleaning time with Turnow-dimples) is far less than the positive influence with respect to the improved heat transfer (105 % increase with Turnowdimples (Turnow et al. 2014)). Especially the Turnowdimples are providing a good cost-benefit ratio with regard to this comparison.

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