Decline in energy efficiency of heat exchangers due to crystallization fouling

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1 Introduction

Heat exchangers are used in industrial processes to transfer energy from one source to another. Heat exchangers improve energy efficiency of processes and thus increase profitability and decrease environmental impact of the production.

Energy efficiency of heat exchangers may be diminished by fouling, in which unwanted material deposits on the heat transfer surface and reduces heat transfer and increases the pressure drop of the system. Due to fouling, energy demand, and operation and maintenance costs of industrial processes are increasing significantly. According to Müller-Steinhagen et al. (2005), the total annual cost due to fouling for highly industrialized countries, such as United States or United Kingdom are about 0.25% of the countries' Gross National Product (GNP).

Mechanical methods have been tried to reduce fouling but they are expensive and not necessary efficient enough. The use of chemical detergents may damage the product and may have negative environmental effects. Thus, the most efficient way to deal with fouling is to prevent it, but this requires the identification of the interactions between different factors that affect fouling. Fouling is a very complex phenomenon in which separate fouling mechanisms, like crystallization, particulate, corrosion and biological fouling may occur simultaneously. Thus, understanding of separate fouling mechanisms is crucial in order to prevent fouling in process equipments.

One important fouling mechanism that occurs in a wide range of industries is crystallization fouling. Crystallization fouling occurs when the concentration of dissolved material in the fluid exceeds the solubility limit leading to supersaturated conditions. Solubility of the inversely soluble salts, like $CaCO_3$, decrease with an increase in temperature, and thus heated surfaces are easily exposed to crystallization fouling.

2 Objectives of the research

In this paper, crystallization fouling of $CaCO_3$ on a heated surface in a laboratory scale set-up of a plate heat exchanger is studied. SEM and XRD are used to quantify the morphology and the composition of the deposited material. Based on the results, the influence of different operating parameters on mass deposition of $CaCO_3$ salts and energy efficiency of the heat transfer equipment are discussed.

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3 Results

Experiments of $CaCO_3$ crystallization fouling are performed in an experimental set-up which contains two stainless steel (AISI 316) flat plate test sections, size of 0.1 m x 0.2 m, which are heated by ohmic heaters embedded in the walls of the test section. The test solution, which is prepared by mixing equivalent amounts of $CaCl_2$ and $NaHCO_3$ salts to deionized water, is circulated to the test section from a mixing tank. Filters (20 µm and 2 µm) are used in the surface crystallization experiments to remove bulk crystallized particles.

3.1 Surface crystallization fouling

Fouling during the experiments is observed from the measured temperature elevation of the surface of the heated test section. The surface temperature increases when the resistive fouling layer grows on the surface which is heated with a constant heat flux. The fouling curve, which describes the change in the fouling resistance, is obtained by dividing the temperature elevation with the heat flux. The slope of the fouling resistance curve represents the fouling rate. Figure 1 presents the fouling resistance curves in the experiments where heat flux (a) and flow velocity (b) are varied.

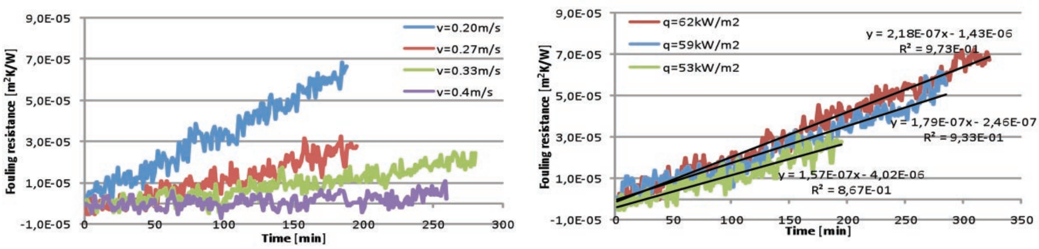

Figure 1 Fouling resistance on the left (a) with different velocities when heat flux is 53 kW/m2 and on the right (b) with different heat fluxes when flow velocity is 0.27 m/s.

Based on the results, increase in the heat flux and the wall temperature augment the fouling rate, and the increase in the velocity decreases the fouling rate. The effect of the heat flux is quite small compared to the effect of the flow rate. However, this might be due to stronger effect of the flow rate on the wall temperature or quite small differences in the studied heat fluxes. The effect of concentration was also studied but it was found to have a minor effect if the fluid is highly supersaturated because crystallization takes place already at the bulk fluid adjusting ion concentration in each experiment to the same level.

Results show that the crystallization, which usually is defined to be a combination of diffusion of the ions to the vicinity of the surface and surface integration (or reaction) of the ions to the surface, seems to be more strongly controlled by temperature than velocity. Thus, it seems that strongly temperature dependent surface integration reaction controls the surface crystallization fouling process.

3.2 Bulk crystallization

The fouling resistance and thus the fouling rate may differ when the filters are not used to remove impurities from the bulk fluid. In the absence of filters, $CaCO_3$ may crystallize already to the bulk fluid whereas in the presence of filters these particles crystallized to the bulk fluid are filtered out of the solution before the heated surface.

The effect of bulk crystallization is studied in two experiments done with similar conditions except for the use of the filters. The results show that the fouling rate is much higher when the filters are not used during the experiment. In further experiments, the dependency of the fouling resistance on flow rate and heat flux is also found to differ from the experiments done with the filters in-line.

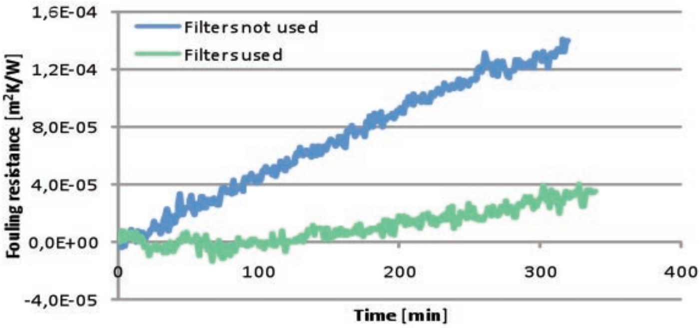

Figure 2 Difference in fouling rate caused by in-line filters.

3.3 Analysis of the deposition

The composition of the fouling layer is also found to be different in the experiments done with the filters installed in-line of the set-up compared to the experiments done without the filters.

Scanning Electron Microscope (SEM) is used to study the morphology of the deposited material, and X-ray Diffraction (XRD) to confirm the composition of the material. Based on the SEM and XRD results, in the presence of filters (Fig. 3, left), the deposited material grows on the surface and mainly orthorhombic, needle shaped aragonite crystals are formed. In the absence of filters (Fig. 3, right), when bulk crystallization occurred, hexagonal, round shaped calcite particles were mainly found in the deposition layer in the studied conditions.

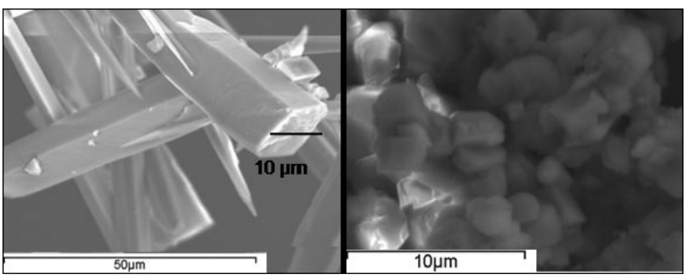

Figure 3 SEM-figures of the fouling layer. On the left, the experiment was done with the filters, and on the right the experiment was done without the filters in-line.

Based on the experimental results and analysis of the deposited material, it seems that in the absence of the filters, the controlling fouling mechanism is the particulate fouling of the bulk precipitated $CaCO_3$ particles where as in the presence of the filters the crystallization fouling by the surface growth is dominating.

3.4 Effect of fouling on the heat transfer efficiency

The ability of heat exchangers to transfer energy is markedly reduced due to fouling. In the studied cases, where heat flux was 53 kW/m^2 and velocity was varied, the average reduction of the heat transfer coefficient during the experiment was 1.62%/h, 0.65%/h, 0.31%/h, and 0.02%/h for the flow velocities 0.2 m/s, 0.27 m/s, 0.33 m/s, and 0.4 m/s, respectively.

4 Relevance of the research

Even in reasonably short laboratory scale experiments, the reduction in heat transfer coefficient due to fouling is significant. The results show that quite small changes in the operating parameters can influence the energy efficiency of the process. In addition, even small amounts of impurities may have a significant effect on fouling, and even change the fouling mechanisms. Thus, especially in complicated industrial processes, it is beneficial to find out all significant fouling mechanisms and their interactions. For this, research on separate fouling mechanisms is essential in order to understand the fouling processes entirely.

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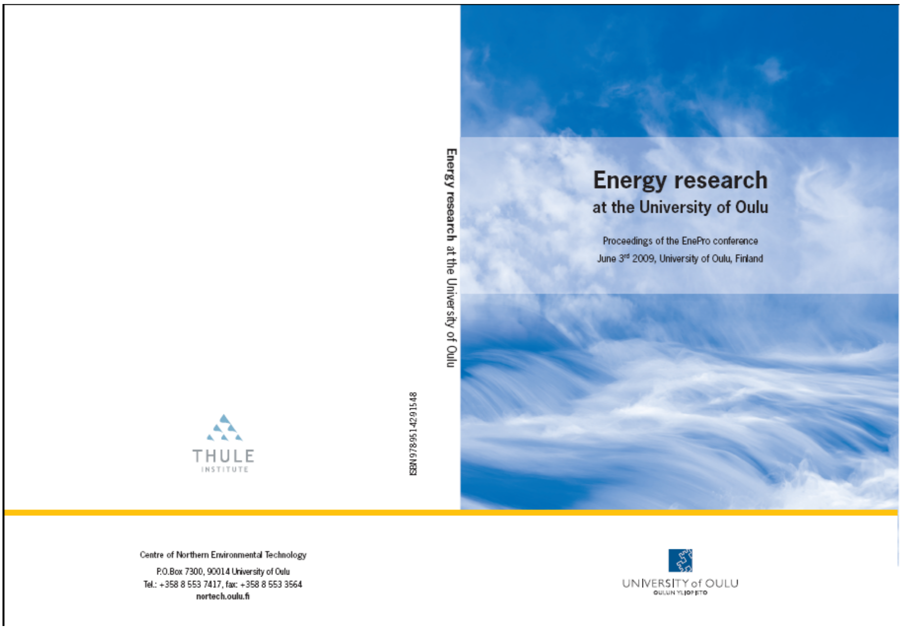

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