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Experimental observation of surface morphology effect on crystallization fouling in plate heat exchangers ☆

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ABSTRACT

In this study, stainless steel test plates with different surface roughness and textures, which are used as the heat transfer surface of a plate heat exchanger, are tested individually in calcium carbonate fouling experiments. The present experimental results clearly indicate a strong correlation between the surface roughness and the amount of crystallization fouling deposit. Through detailed image analysis, four stages of the formation of crystallization fouling are identified, and the impact of the surface morphology on the extent of crystallization fouling is described qualitatively.

1. Introduction

Fouling is the accumulation of an unwanted layer of scale on a surface submerging in a fluid medium. Six different forms of fouling may occur in industrial applications, which include crystallization, particulate, chemical, corrosion, biological and solidification fouling [1–3]. Fouling is a highly detrimental process which has a significant negative impact on the performance of industrial systems. In industrialized countries, fouling costs have been estimated to be as large as 0.25% of the country's gross national product [3]. Therefore, significant effort has been devoted to fouling prevention and mitigation as well as the development of antifouling techniques.

Among the six different forms of fouling, crystallization fouling, which is common in industrial heat exchangers, is responsible for approximately 25% of the scale related issues. Inversely soluble salts such as calcium sulphate and calcium carbonate have been recognized as the most prolific forms of crystalline scale deposit in heat exchangers [1]. Crystallization fouling involves three basic fouling phases [2,3]. The first of the three phases of crystallization is called 'attainment of supersaturation'. Following supersaturation, nanometre scale clusters of dissolved salts then begin to form as nuclei, which become stable once they mature to a critical size. This phase is referred to as the 'formation of nuclei'. The final phase of crystallization is called 'growth of crystals', which involves subsequent development of a variety of larger, variably sized crystal shapes. Bansal et al. [3] revealed five circumstances under which supersaturation, and hence crystallization fouling can occur. In addition, crystallization fouling is affected by factors such as flow velocity, heat and mass transfer, chemical composition of the fluid medium, and material properties of the surface, etc. [4].

The occurrence of crystallization fouling may dramatically reduce the performance of industrial heat exchangers. On one hand, the poor thermal conductivity of the scale deposit slows down the heat transfer rate through the fouled surface. On the other hand, the presence of the unwanted layer of scale deposit in flow channels produces an additional resistance to the flow and increases the pressure drop across the heat exchangers and thus the pumping power of the industrial processes. Accordingly, industrial heat exchangers are commonly overdesigned in order to compensate the loss of efficiency due to crystallization fouling [2]. This method of dealing with fouling is inefficient and uneconomical, and expensive cleaning and removal procedures are desirable at routine intervals.

Plate heat exchangers are among the most cost-effective types of heat transfer devices. They are comprised of flat, corrugated or finned plate-like heat transfer surfaces, which separate hot and cold process fluids, and they can be designed with single or multi-pass configurations in parallel or counter flow arrangements. The plates are generally designed as large as possible to maximize the heat transfer area. Plate heat exchangers are used for a wide range of applications, including food processing, space heating, refrigeration, central cooling systems, automotive applications, power plants, chemical plants, petrochemical plants, petroleum refineries and natural gas processing [5]. However, once fouled, plate heat exchangers become highly unreliable compared to alternative designs. This highlights the need for further study into the fouling of plate heat exchangers.

In the field of biofouling, extensive studies have explored the effects of various microtopographic surface parameters in marine environments, and green and biomemetic antifouling techniques

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have been developed. A recent study of Scardino et al. [6] has revealed distinct correlations between certain surface parameters and the anti-biofouling properties of the surface. Their experiments show that variations in parameters such as fractal dimension, surface roughness, waviness, skewness and texture aspect ratio, can have a strong influence on the rate and degree of biofouling.

Despite that extensive studies have also been undertaken in the field of crystallization fouling, research in this field has not explored the relationship between fouling and surface micro textures to the degree of detail as in biofouling research, and so far mainly the surface roughness effect on crystallization fouling has been reported [7,8]. This highlights the need for further study in this area. The present investigation addresses this issue.

In this study, different surface textures and roughness are produced on stainless steel surfaces of a plate heat exchanger and tested against crystallization fouling. Qualitative observation of the formation of fouling on the plate heat exchanger is carried out based on image analysis. Details of the experiments and experimental results are described in the following sections.

2. Experimental details

2.1. Apparatus

The fouling experiments are conducted on a plate heat exchanger apparatus, which includes a heating tank, a water pump, a plate heat exchanger assembly, a number of control valves, and flow rate and temperature control and measurement systems. Fig. 1 illustrates the configuration and working principle of the plate heat exchanger assembly. The dimensions of the heat exchanger assembly are 200 mm × 120 mm × 80 mm, and the dimensions of the heat transfer plate are 100 mm × 85 mm × 2 mm.

Water in the heating tank is heated directly by electric heating coils, the operation of which is controlled by a thermostat. Hot water at a set temperature is pumped into the plate heat exchanger and circulated through the hot side of the exchanger. The main water supply from a water tap is circulated through the cold side of the heat exchanger and discharged into the drain afterwards. Two rotameters of different flow rate ranges are used to measure the flow rates of the hot- and cold-water flows respectively, and four K-type thermocouples are used to monitor the water temperatures at the inlets and outlets of the hot and cold sides of the plate heat exchanger respectively. The uncertainty of the temperature measurements by the thermocouples is ±0.75 °C over the operational temperature range after calibration.

2.2. Fouling agents

As mentioned above, inversely soluble salts are responsible for crystallization fouling, which occurs mainly on the hot side of heat exchanger surfaces. Calcium carbonate [$CaCO_3$] and calcium sulphate [$CaSO_4$] fouling have been identified as the most prevalent in industrial applications, and thus are the most commonly studied forms of fouling agents. Of these two forms of fouling, calcium carbonate fouling is more prevalent than calcium sulphate fouling, and is chosen as the fouling agent here.

The calcium carbonate fouling additive may be introduced into the hot side solution in two different ways. One way involves directly dissolving calcium carbonate into the hot solution, and the other involves chemically mixing sodium bicarbonate [$NaHCO_3$] and calcium chloride [$CaCl_2$] in the heating tank to produce calcium carbonate [9]. The latter method can produce a significantly higher concentration of a calcium carbonate solution, which will produce faster crystallization fouling, and thus is adopted here. The highest percentage of supersaturation of calcium carbonate reported in the literature is 74% [9]. This value is also adopted for the present experiments.

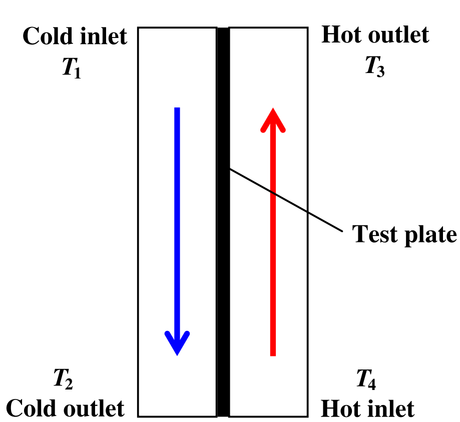

Fig. 1. Illustration of the plate heat exchanger assembly.

2.3. Heat transfer surfaces

The focus of this investigation is on the test plate of the plate heat exchanger assembly (refer to Fig. 1), and the purpose is to test the effects of surface textures and roughness under crystallization fouling. Since stainless steel is commonly used in plate heat exchangers owing to its strength and strong resistance to corrosion, AISI 316 stainless steel is selected as the test material in this study. This material has also been successfully tested by others [1,10]. Two types of surface textures and a range of surface roughness are produced on the stainless steel plates. The first type of surface texture is a mirror smooth surface, which has no particular texture pattern. The other type of surface texture has simple linear and parallel grooves on the surface.

In order to prepare the stainless steel samples with the required surface textures and roughness, roughness testing is carried out prior to fouling experiments, which includes roughening the surface with sandpapers and measuring its roughness. This procedure is carried out using P1200, P600, P400, P320, P240 and P120 sandpapers and a polished surface respectively. A calibrated Mahr Perthometer M1, which is suitable for roughness measurements of most engineering surfaces, is used to measure the surface roughness of the produced samples. A trace length of 17.5 mm is selected for each measurement and a total of 3 parallel traces in the direction perpendicular to the surface textures are performed on the stainless steel test plates. The average roughness value of the three measurements is adopted as the final roughness. The results of the roughness testing are shown in Table 1.

2.4. Fouling experiments

Four experimental runs have been performed, including one with the polished surface and three with linearly textured surfaces of different roughness (refer to Table 1). All experiments are carried out with the hot-water temperature set to 70 °C, and the hot and cold-water flow rates are set to 200 L/h and 600 L/h respectively. Each

Table 1
Roughness values of the stainless steel test surfaces.

Sandpaper grade	Avg. grit size (μm)	Ra_1 (μm)	Ra_2 (μm)	Ra_3 (μm)	$Ra_{avg.}$ (μm)	Test code
Polished					0.073	1
P1200	15.3	0.079	0.084	0.07	0.078	
P600	25.8	0.122	0.1	0.115	0.112	2
P400	35	0.188	0.193	0.18	0.187	3
P320	46.2	0.314	0.311	0.335	0.32	4
P240	58.5	0.513	0.485	0.542	0.513	
P120	125	1.211	1.278	1.295	1.261	