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Influence of thermal shock on fouling of smooth, rough and finned tubes

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ABSTRACT

Deposits of salts and extraneous materials occur during water desalination by heating, forming an insulating layer, which is known as fouling. Fouling reduces the rate of heat transfer between the heating medium and the water, subsequently decreases the desalination efficiency gradually and sometimes can lead to operation failure. The thermal shock is a fouling mitigation technique in water desalination units, which could be due to sudden decrease or increase in the heat transfer process. The objective of this research is to study the removal of fouling layers by the thermal shock in case of (i) smooth tubes, (ii) rough tubes and (iii) finned-rough tubes. It has been found that it is possible to remove the fouling layer by the thermal shock technique in case of smooth and rough tubes, but not in case of finned tubes. The thermal shock blows off the fouling layer in case of plain tubes, and the fouling process resumes after the thermal shock without any delays, i.e. no more induction period. Fins assist the sticking of crystals to the heat exchanger tubes and prevent its removal by thermal shock. Fins act as a heat sink during the thermal shock, which reduces the dissipation of heat to the surrounding water, i.e. cooling of the tubes, and prevent cracking of the fouling layer.

1. Introduction

Desalination is used for many industrial purposes. Desalination is a process that removes salts and other dissolved solids from brackish water or seawater. Several countries rely heavily on desalination, e.g. Saudi Arabia receives more than 70 percent of its drinking water from desalination plants [1]; the British Virgin Islands of Tortola and Virgin Gorda receive almost all of their drinking water supplies from desalination [2]. It is certain that the best way to solve the problem of water shortage is desalting sea and brackish water. There are several methods of desalination in use today. The major methods are categorized into two types: thermal and membrane [3]. In thermal methods heat is applied to the feed water to bring it to a boil and produce steam. The steam then condenses into fresh water, leaving the salts behind in the heating zone. There are two membrane methods of desalination. One method uses an electrical current to attract the salt molecules through a membrane. The other method employs high pressure to force the water through the membrane [4,5] and leaving the salts behind the membrane. Generally speaking, thermal methods are the most widely used worldwide [6]. The performed research is based on thermal desalination, which is desalinating water by heating, but the main problem is fouling. Fouling occurs when salts or minerals build up during water desalination on the heating element, which is known as crystallization fouling [7,8]. Fouling adds a resistance to heat transfer, and causes the rate of heat transfer to decrease and sometimes can lead to operational failure. The net effect of these accumulations on heat transfer is represented by a fouling factor R_f [9], which is a measure of the thermal resistance introduced by fouling.

Several mitigation techniques have been developed to minimize crystallization fouling. The main methodologies for mitigating fouling in industrial heat exchangers have been summarized by Müller-Steinhagen et al. [10], and it is advised that the proper way to mitigate fouling is firstly by a proper design and secondly by online mitigation techniques. One of these online mitigation techniques is to inject projectiles [11], e.g. sponge balls, through the heat exchanger tubes to remove deposits. Abd-Elhady et al. [12,13] found that the cleaning action of projectiles is relatively profound at the beginning of the fouling process and decreases as the fouling layer builds up until it diminishes to zero when the asymptotic

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behavior is approached [14]. Mitigating fouling using projectiles is a promising technique but it can only be used to clean tubes from inside. Eslamian et al. [15] developed a cleaning method of fouling deposits using a supersonic air jet. Eslamian et al. [15] found that soft deposits can be broken by any jet type, while harder deposits, especially those farther from the nozzle exit, require a longer exposure time to be broken. The cleaning method developed by Eslamian et al. [15] requires the shutdown of the desalination plant and then removal of the deposit by the air jet and cleaning of the whole desalination plant, which could be not acceptable from an operational point of view. Föste et al. [16] developed a cleaning method of fouling deposits using pulsed flow. Föste et al. [16] found that the pulsed flow leads to shorter induction periods as well as decreased final fouling resistance. They found that the decrease of the final fouling resistance is due to the increased fluid forces. It can be concluded from their work that the pulsed flow is a good mechanism to mitigate fouling still it does not prevent fouling. Bucko et al. [17] developed a cleaning method of fouling deposits using ultrasound, such that they used two different configurations, direct and indirect method of coupling the ultrasound into the microstructures. In the direct method the ultrasonic sonotrod is directly connected to the housing of the microstructured heat exchanger but in the indirect method the ultrasonic sonotrode is placed in the front of the microstructure. Bucko et al. [17] found that the best results were obtained for cleaning with the indirect ultrasound method. This method is expensive because the ultrasonic sonotrode should always be connected with the microstructured heat exchanger.

Among the developed fouling mitigation techniques is the thermal shock [18], which could be due to sudden decrease or increase in the heat transfer process. Thermal shock [18] can affect materials by causing excessive temperature gradients on them, which results in excessive thermal stresses. Thermal stresses can be tensile, which is defined as a stress resulting from forces acting in opposite directions tending to pull a material apart that can lead to material breakage. Thermal stresses can be due to non-uniform heating or cooling of a uniform material, which is the case if the heating process during desalination is stopped suddenly and the fouling layer has become totally sintered [19], i.e. rigid and not porous. The difference in thermal expansion between the surface substrate and the deposit layer plays a key role in the thermal shock process. The tubes of the heat exchanger will contract more than the fouling layer during desalination if the heating process is stopped suddenly, i.e. a thermal shock is applied, and that is due to the difference in the coefficient of thermal expansion of the heating coil and the fouling layer, which can lead to cracking and separation of the fouling layer from the tubes of the heat exchanger. It has to be mentioned that experimental results on the influence of the thermal shock on fouling of heat exchangers is scarce. Evangelidou et al. [20] studied the influence of thermal shock on fouling of various structured tubes [21], i.e. finned tubes, during pool boiling of $CaSO_4$ solutions. They found that thermal shock cannot crack and peel off the fouling layer in case of structured tubes, but it is very effective in case of plain tubes. Abd-Eltwab et al. [22] studied experimentally the minimum temperature of the heating oil in water desalination units as a function of the material of the heat exchanger tubes. They found that the minimum heating oil temperature that allows the applicability of the thermal shock is 130 °C in case of using copper tubes, and 140 °C in case of stainless-steel tubes.

In the present research the influence of the thermal shock on fouling as a function of the surface roughness of the heat exchanger tubes is examined experimentally. An experimental setup has been developed to conduct this research, such that the influence of the thermal shock on fouling in water desalination units is studied. The experimental setup consists of an oil tank in which oil is heated by an electrical heater. The hot oil is circulated via a gear pump to a water tank, which contains the water to be desalinated, i.e. a $CaSO_4$ solution. The water is heated and converted into steam by the hot oil leaving the salts behind, i.e. the fouling layer, on the tubes of the oil's heating coil. A thermal shock is applied when the asymptotic behavior is approached, such that the flow of the hot oil is suddenly stopped for 5 min and then resumed. The experimental setup used in this research and the experimental procedure are explained in the next section followed by the experimental results and discussion, and eventually the conclusions.

2. Experimental setup and experimental procedure

2.1. Experimental setup

A schematic of the experimental setup, i.e. the desalination unit, is shown in Fig. 1. The water desalination unit consists of an oil tank, i.e. 500 mm × 250 mm × 200 mm, in which oil is heated by an electrical heater of 3 kW heating power. The hot oil is circulated via a gear pump to a water tank of dimensions 600 mm × 250 mm × 20 mm. Inside the water tank is the water to be desalinated, i.e. a $CaSO_4$ solution, which is heated and converted into steam by the hot oil. Heat is transferred from the hot oil to the water in the water tank via the heating coil inside the tank, as can be seen in Fig. 1. The $CaSO_4$ solution is prepared separately based on the technique adopted by Esawy et al. [19], and then added to the water tank. The generated steam is condensed into fresh water using the water condenser shown in Fig. 1. The oil returns back to the oil tank for reheating and a new cycle of desalination begins.

The heating coil consists of horizontal tubes of diameter 12 mm, length 200 mm and the number of tubes is 8. The tubes of the heating coil are parallel to each other such that the free distance between the tubes is 30 mm, and the tubes are connected at the ends, as can be seen in Fig. 1. Thermal oil, Mobil-Therm 605 [23], has been used in the performed experiments. The density of the thermal oil is 880 kg/m^3, specific heat capacity is 2.9 kJ/kg K, kinematic viscosity at 40 °C is 3.2×10^{-5} m^2/s and the boiling temperature of the oil is 300 °C. The temperature of the oil has been measured at the inlet and outlet of the heating coil inside the water tank, i.e. $T_{oil,in}$ and $T_{oil,out}$, respectively. Also, the temperatures of the outer surface of the heating coil, T_s, as well as the temperature of the water in the water tank, T_w, are measured. Thermocouples of type k [24] have been used to measure the temperature of oil, water and the surface temperature of the heating coil. The thermocouples have been calibrated in the Institute of Measurement and Calibration in Egypt [25]. A glass window is installed at the side of the water tank, as shown in Fig. 1, in order to visualize the development of the fouling layer during the performed experiments.

2.2. Experimental procedure and data reduction

The thermal shock experiment has been applied for three different types of tubes of the heat exchanger; (i) smooth tube, (ii) rough tube and (iii) rough-finned tube. All tubes are made from stainless steel. Smooth tubes are used in the first set of experiment, and an image of the smooth tube is shown in Fig. 2. The desalination process is continued until an asymptotic fouling behavior is approached [19], i.e. no more increase in the thermal resistance R_f of the fouling layer, and then the thermal shock process is applied. The thermal shock is applied by turning off the oil heaters for 5 min, and then resuming the heating process. The thermal resistance R_f is calculated from the overall heat transfer coefficients at clean and fouling conditions as follows,