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Research Paper

A study on the reduction of $CaCO_3$ fouling in hot-water storage tank by short pulse plasma application (rev 1 yc)

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ABSTRACT

The present study investigated the feasibility of using plasma spark discharge to prevent mineral fouling on the coil heat exchanger in a hot-water storage tank, which is used in a large heat pump system. Experimental fouling test was conducted with spark discharges produced directly in water inside the tank. The overall heat transfer coefficient was determined from both flow rate and four temperatures measured at the inlet and outlet of the coil heat exchanger. The artificial hard water was used to accelerate the fouling process on the heat exchanger surface. The test results showed that the fouling in the coil heat exchanger was effectively suppressed using plasma application. For the case of 1250-ppm solution, the fouling resistance was reduced by 66% with plasma application compared with no-treatment case. The spark discharge plasma application can be a useful method to reduce the mineral fouling on the coil heat exchanger in a hot-water storage tank.

1. Introduction

The present study deals with the prevention or mitigation of mineral fouling caused by hard water in the coil heat exchanger in a hot-water storage tank system, which is used in a large heat pump system. The hard water is characterized by high concentrations of mineral ions such as calcium and magnesium [1]. In particular, calcium carbonate ($CaCO_3$) fouling is one of the most common fouling problems in a heat exchanger, which occurs due to the inverse solubility of $CaCO_3$ with temperature [1,2]. The deposition of $CaCO_3$ particles on heat exchanger surface increases with time as the cold water is continuously heated inside the heat exchanger. If the crystallization reaction of $CaCO_3$ takes place on the heat transfer surface as in untreated hard water, a precipitation fouling takes place, resulting in a hard tenacious scale on the surface [3]. Since the thermal conductivity of $CaCO_3$ is very small (e.g., 2.25 W/m K) [1], such a scale deposit behaves as an insulating layer, thus reducing the heat transfer performance of the heat exchanger. Accordingly, the prevention or mitigation of fouling in the heat exchanger is one of the major goals in the design and operation of a hot-water storage tank system.

More recently, a number of researchers studied fouling problems in convective boiling of dilute CuO nanofluids with suspended CuO nano-particles [4,5] and of $CaSO_4$ aqueous solutions [6]. They reported the fouling resistance with dilute CuO nanofluids at various levels of concentrations rapidly reached an asymptotic value of 0.9 m^2 K/kW within 200 min of heat transfer test [4,5], indicating that although the nanofluids initially help increasing the heat transfer performance, the fouling problems associated with the nanofluids may negate the initial benefit of the enhanced heat transfer.

The performance loss of a heat exchanger due to fouling can be very significant. For example, after 5 years' operation, the performance can be reduced by about 50–90% compared to that of the initial clean heat exchanger [3]. Especially the heat exchanger in the hot-water storage tank often shows a serious fouling problem due to (1) the large temperature difference between tubeside and shellside and (2) a low flow velocity in the shellside [7]. The conventional fouling control methods include mechanical cleaning, chemical water treatment [8,9], and electric or magnetic field applications [10,11].

Recently, plasma spark discharge was used for the prevention of mineral fouling in a condenser in cooling water application [12,13]. Spark discharge has a very short pulse of 10–50 ns with a peak voltage of 30 kV, which produces UV, plasma species [such as radicals ($H^\cdot$, $O^\cdot$, $^\cdot OH$) and molecules (H_2O_2, O_3, etc.)], and shock wave [13,14]. In addition, the spark discharge produces an intense local

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Nomenclature

A	heat transfer area, m^2
C_p	specific heat, J/kg K
HEX	heat exchanger
$\dot{m}$	mass flow rate, kg/s
$\dot{Q}$	heat flow rate, kW
R	thermal resistance, m^2 K/kW
T	temperature, °C
U	overall heat transfer coefficient, kW/m^2 K

Subscripts

c	cold water
f	fouling
h	hot water
i	inlet or initial clean surface
lm	log mean
o	outlet

heating, which is instrumental in the dissociation of bicarbonate ions, thus triggering the formation of $CaCO_3$ particles in bulk water, rather than in the surface of heat exchanger. Although the suspended $CaCO_3$ particles in water eventually adhere to the heat transfer surface, the scale formed on the surface of the heat exchanger is of a soft-sludge type, which is typical in particulate fouling [3,15].

Furthermore, the spark discharge produces strong shock waves in water, which impinge on the fouled heat transfer surface, removing the scale deposits [12]. The plasma discharge consumes relatively small energy, i.e., approximately 2 J per pulse [16]. Although the plasma spark discharge was shown to be useful in the mitigation of mineral fouling in a condenser in cooling water application, the temperature difference in a hot-water storage tank is significantly greater than that in the condenser. Furthermore, the flow velocity in the condenser is significantly larger than that in the hot-water storage tank [17]. Note that the flow velocity inside the hot-water storage tank is so slow such that one has not only a plug flow but also a thermally stratified flow pattern in the hot-water storage tank, a tough environment to prevent mineral fouling. Thus, it is not clear whether the spark discharge will be useful in the mitigation of mineral fouling in the hot-water storage tank.

Therefore, the objective of the present study was to experimentally investigate whether or not the plasma spark discharge could prevent or mitigate mineral fouling when hard water is used in the coil heat exchanger in a hot-water storage tank.

2. Experimental devices and method

Fig. 1 shows the schematic diagram of the present experimental facility, which consisted of a hot-water storage tank, a coil-type heat exchanger, an electric heater, multiple thermocouples with analog–digital data acquisition system, flow meters, a pressure gage, and a plasma spark discharge system with a high-voltage power supply. The diameter and height of the hot-water storage tank were 400 and 600 mm, respectively. A coil heat exchanger made of copper tube (outside diameter = 15.88 mm and length = 10 m) was positioned inside the hot-water storage tank to heat cold hard water flowing in a once-through mode in the tank.

An electric heater of 6 kW was used to supply the hot working fluid at 95 ± 1 °C to the inlet of the coil heat exchanger (i.e., tubeside). The mass flow rate for the hot water was determined for the outlet temperature of the hot water to be about 70 °C. Both inlet and outlet temperatures were continuously measured and recorded throughout the test. Of note is that such a high temperature of the working fluid was necessary for calcium carbonate fouling to develop on the outside wall of the coil heat exchanger within a reasonable time period.

Fig. 2 shows the conceptual diagram of a plasma spark discharge system, which consisted of a high-voltage power supply, a capacitor, an air spark gap, and a high-voltage electrode submerged in water. A short pulse of high voltage is necessary to produce a powerful spark in water [18,19]. Among a number of different types of electrode geometry used to produce spark discharges in water, the most common method is a point-to-plane geometry with a sharp tip at the high-voltage electrode [19], because this geometry can produce a high intensity spark in water with a relatively low voltage (i.e., 3 kV) [19]. The present study also utilized the point-to-plane geometry with a high-voltage point electrode, which was positioned 300 mm below from the top of the hot-water storage tank. The high-voltage electrode was positioned close to the coil heat exchanger (i.e., at 2–3 mm), whose surface was used as the base ground plane (i.e., cathode).

The three different concentrations of calcium hardness as $CaCO_3$ (i.e., 500, 750, and 1250 ppm) were used in the artificial hard water. Note that the concentrations in the study were significantly greater than that in the natural hard water (i.e., about 100–200 ppm). In order to make the artificial hard water, two separate solutions of $NaHCO_3$ and $CaCl_2$ were prepared in two separate water tanks (see Table 1 for more details). Then, the two solutions were mixed together just prior to being pumped to the hot-water storage tank as shown in Fig. 1. The inlet temperature of artificial hard water to the hot-water storage tank (i.e., shellside) was maintained constant throughout the fouling test to be 30 ± 1 °C by using a small electrical heater installed for this purpose (see Fig. 1). Both inlet and outlet temperatures were continuously measured and recorded throughout the test.

The high concentration hard water was used to accelerate the fouling process in the present study so that each test could be completed within 20–60 h. The cold hard water was circulated through the hot-water storage tank in a once-through flow mode and discharged to drain such that the fouling built up on the outside surface of the coil heat exchanger.

Note that the electric conductivity of the artificial hard water was greater than ~4000 microS/cm for all three concentration solutions due to large amounts of Na^+ and Cl^- ions (see Table 1). When the electric conductivity of water is very big (i.e., >4000 microS/cm), it is not easy for a short spark pulse to be generated, as electrons are leaked from the high-voltage electrode to water prior to the initiation of the pulse [19]. In order to improve the spark generation in this high conductivity solution, an air-spark gap was used with a relatively small air-gap distance (see Fig. 2). Furthermore, the gap distance between the sharp-tip anode and the surface of coil heat exchanger (i.e., used as the cathode) was a critical parameter to produce powerful spark discharges in the present experiment. The optimum gap distance in the present test was found to be between 2 and 3 mm.

The flow rate of the artificial hard water was continuously monitored with an electromagnetic-type flow meter (Model number: VN05, Aichi Tokei Denki Co., LTD, Japan) so that the flow rate could be maintained constant at 0.0167 kg/s throughout the test by slightly adjusting a flow-control valve.