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Fouling and fouling mitigation on heated metal surfaces

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ABSTRACT

An apparatus was built to study heat transfer fouling on different heat exchanger pipe surfaces by visually observing the progressive fouling deposition under the same solution conditions. Test pipes were centrally located in a cylindrical tank with a concentric vertical agitator to give constant and uniform flow conditions near the pipe surface. Pipes with either smooth or roughened surfaces provided quantitative data on the progressive build-up and the composition of the deposits. The calcium sulphate deposition on four different metal surfaces (copper, aluminium, brass, and stainless steel) was investigated. The results show that fouling increases with time but at a decreasing rate over set intervals. The deposition also increases with the increasing thermal conductivity of the metal, or the total surface energy. Chemical reaction fouling along with particulate and crystallisation fouling occurred on reactive surfaces when corrosive chemicals were used, and this was compared with crystallisation-only fouling on non-reactive surfaces. Bleached Kraft softwood pulp fibres at various concentrations were added to the fouling solution to study their affects on fouling on the hydraulically smooth pipes. Fouling was retarded with only a low fibre concentration and reduced further as fibre concentration was increased.

1. Introduction

Mineral scale formation on heat exchanger surfaces rapidly increases the thermal resistance and reduces operating service life. Panchal and Epstein [1,2] categorised 5 types fouling (biochemical interaction, chemical reaction, particulate, crystallization, and corrosion fouling), and 5 deposit steps (generation, transportation, attachment, removal, and aging). Panchal [1] also mentioned that crystallisation fouling is formed by the deposition of salts on the surface by attraction. Hasson [3] reported that asymptotic deposit behaviour observed for mixed salts may be different from solutions of only single salts. Tlili et al. [4] using a gold-layered nickel foil found that calcium sulphate concentration has a stronger effect than temperature in the precipitation process. Demopoulos [5] reported that supersaturation is the important controlling parameter of aqueous precipitation. Mwaba et al. [6] experimentally investigated calcium sulphate deposition on a flat plate and observed that nucleation started on the downstream side and then propagated upstream. They also observed that the rates of nucleate-front propagation and scale layer growth increased with the surface temperature and decreased with the flow velocity. They have defined super saturation as the ratio of the bulk concentration C_b to the saturation concentration C_s. They also stated that crystalline calcium sulphate forms on the surface as Gypsum ($CaSO_4 \cdot 2H_2O$) in the temperature range of 40 °C to 98 °C. A change of 10 to 20% in induction time was observed while experimenting with a copper plate at a Reynolds number of 23,000, initial $C_b = 3.0$ kg/m^3 and bulk temperature T_b of 40 °C.

Al Mutari [7] noted the increase of fouling deposition rate of $CaSO_4$ with the increase of concentration of the fouling solution. Amjad [8] studied gypsum deposition on various metal surfaces and found that the order of the rate of deposition on different metals as; copper > brass > stainless steel. It is reported that molecules or atoms at the depositing surface interact with those of the solution and the types of forces or interactions depend on the chemistry of both the surface and the fouling liquid [9]. Generally the lower the surface free energy of the depositing surface, the weaker the adhesion of deposit on it [10]. Low-energy surfaces are more resistant to build-up of fouling and easier to clean due to weaker binding at the substratum–liquid interface [11]. Fouling occurs when the total interactive force is negative [12]. Zhao and Muller-Steinhagen [12] described surface free energy (surface tension) as a direct measure of intermolecular forces that affect the attraction of the bulk liquid to the surface layer. Gill and Nancollas [13] studied crystallisation of calcium sulphate on different metal surfaces using a constant heat flux method. They observed more deposition with metals of higher thermal conductivity. They reiterated that the metals with the higher thermal conductivity yielded higher initial steady-state temperatures in the order of Cu > Al > Brass > Stainless steel 304.

Surface roughness leads to a much larger effective contact area than the projected surface area and hence deposit adhesion is stronger [14]. Surface roughness may also enhance the initial deposition

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rate by providing sites for crystal nucleation [15]. Yoon and Lund [16] reported that no surface roughness effect was found in the Ra (the arithmetic mean of the departure of the measured roughness profile from the mean line value) value range of 0.08 to 0.60 μm. McGuire [17] and McGuire and Swartzel [18] in contrast showed that surface roughness was not a factor for fouling with their surfaces having Ra values of 0.04, 0.41, 1.93 and 2.31 μm for polished SS, rough SS, PTFE coating and alumino-silicate coating respectively. Herz et al. [19] also confirmed that calcium sulphate deposition was strongly affected by the degree of surface roughness and the fouling layer on a rough surface was more tenacious than on a smooth surface. They also stated that the higher roughness causes shorter induction periods.

Zhao and Muller-Steinhagen [12] treated metal heat exchanger surfaces with selected elements by ion implantation, sputtering, electrolytic deposition (or a combination of these). The fouling resistance was reduced by up to 78% when $CaSO_4$ was used.

Junghahn [20] reported that the free-energy change associated with crystal nuclei formation was much less on a rough surface than on a smooth surface. Other authors [21,22] however, reported higher deposition rates on rougher surfaces. Gunn [23] investigated 304-stainless steel tubes with different degrees of roughness corresponding to the bonded particles at 80, 120, 180 and 320 Tyler mesh. He maintained the steady-state temperatures of the tube surface and the bulk liquid at 97 °C and 95 °C respectively and observed that the rate of nucleation increased with increasing surface roughness.

Some anti-foulants have been successful in preventing fouling but some have caused undesired product contamination or adverse environmental effects. There are some limited methods for reducing fouling by changing plant operational parameters using techniques such as electromagnetic, electrostatic and acoustic fields, ultraviolet light, radiation or catalytic treatments. The results have been mixed and the outcomes inconclusive.

The present work is in line with environmental-friendly procedures by adding solid, biodegradable fibre to a fouling liquid to mitigate fouling of metal surfaces. Calcium sulphate dihydrate ($CaSO_4{\cdot}2H_2O$) scale formation on different heat exchanger surfaces from aqueous solutions have been studied in a reproducible experimental set-up. The effect of bleached Kraft softwood fibre [24] on $CaSO_4{\cdot}2H_2O$ scale formation from metastable supersaturated solutions was also been investigated in single-pipe SS heat exchangers at different flow rates, salt concentrations and temperature differences. Wood pulp fibres at various concentrations were discovered to mitigate fouling and reduce the deposition rate, showing that the life of a heat exchanger could be prolonged.

The study of fouling on different metal surfaces in a shear field approaches the reality of heat exchangers used in industry. The present work reports the (visual) history of fouling deposition of calcium sulphate with time under the same conditions of heat flux with different types of pipes and surface finishes. It compares crystallisation fouling on stainless steel and aluminium surfaces as well as crystallisation and corrosion fouling on copper and brass surfaces. Interactive effects of particulate and corrosion fouling are also recorded along with the additional effects of fibre in the fouling solution.

2. Experimental

2.1. The apparatus

The schematic diagram of the experimental apparatus is presented in Fig. 1. It consists of two flow loops and a stirred tank containing the fouling solution and test pipe. One flow loop comprises a centrifugal pump, rotameter, a replaceable pipe and test section, and a thermostatically controlled water bath to maintain the heating water at a more or less constant temperature (55 ± 1.5 °C). The hot- water recirculation centrifugal pump (Little Giant Pump Co., USA) can operate at 37 L/min with a maximum head of 4.5 m [130 W, 2,400 rpm motor]. Full details are given in the PhD thesis by Kazi [25].

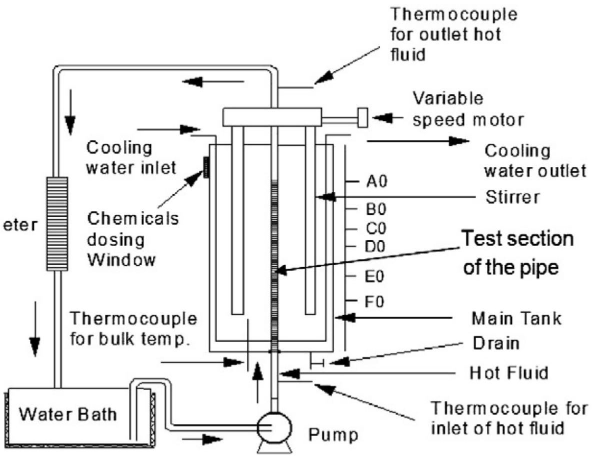

Fig. 1. Schematic diagram of the test apparatus.

The other flow loop is a simple 6 mm diameter copper coil for once-through mains cooling water for keeping the bulk temperature at the required value. The temperature drop over the test section was approximately 2.5 °C.

The fouling solution is contained in the agitated Perspex (Lucite) cylindrical tank, 202 mm diameter and 807 mm high. The tank capacity at the top mark is 17.5 L. It is graduated from a top mark on the tank; designated A0, (594 mm from the bottom). Other level markings from the top A0 are: B0, C0, D0, E0 and F0, which are 90, 162, 234, 342 and 414 mm respectively below the top A0 level. The marks were used to locate the fouling sections after different periods of time as the tank level was sequentially dropped to those marks as the experiments progressed.

The stirrer of the tank is an inverted U-shaped PVC impeller with two wings (dimensions 660 mm long × 16 mm wide × 4 mm thick). The speed of the stirrer is controlled with a variable speed drive. The system is isolated from the atmosphere. The bulk fluid temperature was controlled to within ± 1 °C.

2.2. Test specimens

The experimental test pipes are 1200 mm in length each with a wall thickness of 1.2 mm and an outer diameter of 12.7 mm. These include four metal pipes (stainless steel SS 316, brass, copper, and aluminium) of the same dimensions. Test pipes made from these materials were connected directly and vertically to the outlet pipe from the pump, through a seal at the centre of the tank base, and then to the return pipe at the top above the tank. The test length of each pipe was the actual submerged length between the inside base of the tank and the solution surface, which was lowered sequentially during each experimental run.

The smooth test specimens (Table 1) were used in the as-received condition but before installing in the test rig they were cleaned by rubbing with a water-soaked cloth and flushing with hot water to remove any deposits of grease, oil etc.

Table 1
Hydraulically-smooth and roughened test pipes.

Smooth specimen	μm Ra	Roughened specimen	μm Ra
SS 316	0.245	SS 316	0.88
Brass	0.47	Brass	2.30
Copper	0.25	Copper	2.80
Aluminium	0.22	Aluminium	2.90