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Mitigation of heat exchanger fouling in industry using catalytic materials

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ABSTRACT

Calcium sulphate is one of the major fouling that lead to serious operating problems in industries. The mitigation of calcium sulphate scaling by physical water treatment (PWT) in an operating heat exchanger using zinc and tourmaline as catalytic materials is presented in this paper. The PWT is defined as a non-chemical effective fouling retardation method which exhibits promising protection to protect the environment and maintain a green environment. Catalytic materials such as (zinc and tourmaline) are capable of tackling fouling problems. Experiments were conducted in this study to verify and evaluate the performance of the PWT method. Artificially hardened water at 300 mg L^{-1} was used as the cooling water for deposit analysis. The velocity of the cooling water (i.e. hard water) was varied from 0.3 to 0.8 m s^{-1} and the bulk temperature of the solution was maintained at 45°C. The experimental running time was set at 10 h each step. The artificially hardened water concentration was monitored under various velocities. Complex metric titration was implemented to measure the concentration of calcium sulphate every 2 h for cases with and without PWT-treated cooling water flow. The results showed that the reduction in calcium sulphate formation for case with PWT higher compared to those without PWT. However, it was observed that the performance of the PWT decreases gradually overtime, which needs to be addressed in future work.

Keywords: Fouling; Heat exchanger; Fouling mitigation; Calcium sulphate; Catalytic materials

1. Introduction

Fouling is often described as unwanted material on a heat transfer surface in industries, desalination plants and domestic equipment, which diminishes heat transfer and increases pressure drop in the process [1]. Fouling is a major challenge which needs to be addressed in the design and operation of heat exchangers. Crystallization fouling is one of the fouling mechanisms which is detrimental to the performance of heat exchangers and occurs in a wide range of industrial applications. Crystallization fouling is caused by dissolved salts which precipitate out of the solution due to supersaturation [2]. Supersaturation occurs either by heating the solution above its limiting temperature or increasing its concentration by evaporating the solution above its solubility limit [3]. Calcium sulphate ($CaSO_4$) scaling is the most common

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crystallization fouling which occurs in cooling water applications. Water with high mineral salt concentrations is used to develop fouling on the heat exchanger surface. Hard water management is one of the major concerns in industrial applications as it decreases the performance of heat exchangers. It is, therefore, crucial to maintain the hardness of cooling water at low levels, which in turn, prevents a decrease in heat exchanger performance. The inverse solubility of calcium sulphate results in salt deposits on the heated surface due to the dissolved state of the solution. Crystallization fouling is typically defined in two main steps, i.e. the transport of ions from the bulk fluid to the vicinity of the surface and the attachment of the deposit material onto the surface [4].

In crystallization fouling, crystallization takes place in the bulk fluid as well as on the surface of crystallization. Bulk crystallization in supersaturated solutions may occur spontaneously (primary nucleation zone) or it may require seeds or impurities in the solution (metastable zone) which depends on the pH value and concentration of the solution [5]. When spontaneous nucleation occurs, minute structures form from the collision of two molecules, followed by collision with a third molecule and so on. The lattice structure builds up eventually after the formation of short chains or flat monolayers. The formation of crystals continues in a rapid fashion because of the high local supersaturation. Even though most of these unstable sub-nuclei redissolve, these sub-nuclei stabilize if they grow beyond a certain critical size under average supersaturation conditions in the bulk fluid. These crystals will begin to grow into crystals of visible size. In most cases, the traces of impurities are the primary reason for nucleation in the bulk fluid, since the overall free energy change associated with heterogeneous nucleation is less than that for spontaneous nucleation [6].

Calcium sulphate precipitation on a heat transfer surface lowers the efficiency of heat exchangers due to increased resistance, which eventually increases energy consumption due to retardation of effective heat energy transfer [7]. The thermal conductivity of calcium sulphate is relatively low (i.e. $2.9\,\mathrm{Wm^{-1}\,K^{-1}}$) which increases the temperature of the tube wall due to retardation of heat transfer. The prevention of mineral scale build up within the condenser is also a great concern. The precipitated solid deposits on the heat transfer surface increases the heat transfer resistance and subsequently decreases the thermal efficiency of the equipment [8]. Thus, chemical additives are often used to reduce scaling on a heat transfer surface. However, there are several drawbacks associated with the use of chemicals as they are expensive and pose environmental hazards. Hence, physical water treatment (PWT) methods have been proposed to solve fouling problems and include the use of permanent magnets [9], catalytic material alloys [10], solenoid coil devices [11] and natural fibres [12]. In this study, PWT method is implemented to address the fouling problem by means of catalytic alloys (in particular, zinc and tourmaline as the catalytic materials) in order to mitigate calcium sulphate fouling on an operating heat exchanger. The major advantage of PWT method is because of its eco-friendly environmental characteristic [13].

Numerous studies have been carried out to investigate the efficacy of catalytic alloys in solving calcium carbonate scaling by controlling scale formation from dissolved impurities. MacAdam and Parsons investigated the effectiveness of calcium carbonate precipitation using copper and zinc [14]. They observed that $5\,\mathrm{mg\,L^{-1}}$ of zinc reduces fouling by 35%, which indicates that zinc is an effective inhibitor. Tai and Chien showed that the induction period could be prolonged by adding magnesium ions in the fouling solution [15]. Yang et al. discovered that the addition of $2\,\mathrm{mg\,L^{-1}}$ of zinc retards deposition of calcium carbonate fouling in the system significantly [16]. Based on the findings of previous studies, it is evident that crystallization fouling is significantly influenced by a variety of parameters [17]. For example, the operating conditions (flow velocity, wall and bulk temperatures) [18], solution properties (salt, degree of supersaturation) [19] as well as the geometry of the system (thickness of the laminar boundary layer, shear forces) [20] influence the formation of deposition layer on the heat transfer surface. In general, it is not possible to investigate the effects of all crystallization fouling factors, and the investigation needs to be limited within a specific scope. Nevertheless, it is imperative to investigate the influence of such factors in order to inhibit crystallization fouling as well as provide a detailed model of the fouling process.

In this study, the PWT method is implemented to retard calcium sulphate fouling in an operating heat exchanger, whereby tourmaline and zinc are used as the catalytic alloy materials. The catalytic materials are used to activate heterogeneous nucleation in the treatment process. Catalytic reaction occurs when the water comes in contact with the catalytic material during heat exchanger operation. The surface of the catalytic material (primarily tourmaline) acts as a platform for the dissociation of sulphate ions in water [21]. Hence, this study is focused on evaluating the effectiveness of the catalytic materials in mitigating calcium sulphate scaling.

2. Methodology

2.1. Facility

An experimental rig was designed and fabricated specifically for this study. The catalytic materials consist of zinc and tourmaline placed in a device. Experiments were performed to verify the effectiveness of catalytic materials in solving the fouling problem by varying the water flow velocity and monitoring salt concentrations in the solution (i.e. calcium concentration and calcium sulphate hardness).

A schematic of the experimental rig for fouling experiments is shown in Fig. 1. The flow velocity was controlled using a centrifugal pump (submersible pump) and was divided into two flow loops, namely hot flow and solution flow, as indicated by the red and blue arrows, respectively. A prototype heat transfer test section was used in this study. The inner and outer tubes were made of copper and quartz crystal pipe, respectively, having a diameter of 15 and 38 mm, respectively. The temperature of the solution in the heat transfer section was maintained at 45 ± 1°C. Water heater was used to heat the solution to the desired temperature and thermocouples were used to monitor the solution temperature.

A control valve was used to regulate the flow velocity of the solution, i.e. 0.3, 0.5 and 0.8 $m\,s^{-1}$. A plastic rotary flow metre was used to monitor the flow velocity of the system. In addition, the system was equipped with a bypass feature, which enables experiments to be carried out with and without PWT. The inset of Fig. 1 shows the catalytic materials contained within the device. It shall be noted that the casing is made of zinc and the tourmaline stones are placed within this casing. The outermost casing is made of aluminium.

2.2. Methodology

Fouling test was conducted to determine the performance of the catalytic materials. Leakage test was performed prior to experimental runs to ensure smooth flow conditions. Following this, the system was cleaned by circulating distilled water and chemical clean agents to ensure repeatability and reproducibility of the data.

The solution temperature was maintained at 45 ± 1°C. Artificial hard water was prepared using a mixture comprising 10.41 g of calcium nitrate tetrahydrate $Ca(NO_3)$ and 6.26 g of sodium sulphate (Na_2SO_4) powders diluted in 25 L of distilled water. Calcium sulphate is formed due to the reaction between calcium nitrate tetrahydrate and sodium sulphate in water, as shown in Eq. (1).

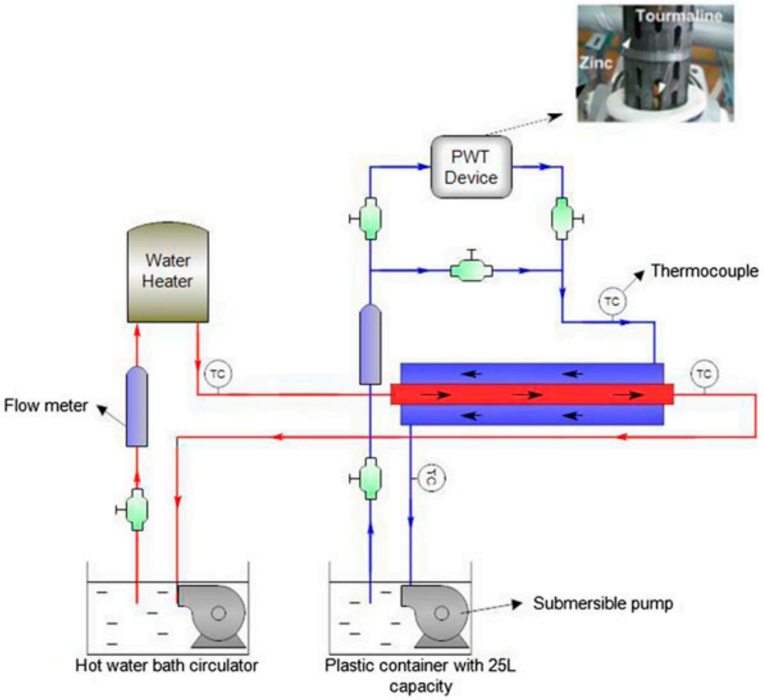

Fig. 1. Schematic of the experimental rig for fouling experiments.

$$Ca(NO_3)_2{\cdot}4H_2O + Na_2SO_4 \rightarrow CaSO_4{\cdot}2H_2O + 2NaNO_3 + 2H_2O \tag{1}$$

The solution hardness was maintained at a constant value of 300 ± 30 mgL^{-1} for each experimental run. The inlet temperature of the cold water flowing through is 25 ± 1℃ and the hot water is at 45 ± 1℃, and temperatures were measured using four thermocouples type K located at both the inlet and outlet of hot water flow and solution water, respectively. The velocity of the hot water flow running through the copper tube is at a constant velocity of 0.3 m s^{-1} and the velocity of the solution flow varied from 0.3 to 0.8 m s^{-1}. The time for each of the test was 10 h for each run. The test rig was cleaned through with distilled water after each test. An additional experiment was performed with the device over a period of 75 h to investigate the performance of catalytic material in fouling mitigation. In order to observe the fouling behaviour on the metal surface under both cases, the fouling resistance R_f was calculated using Eq. (2):

$$R_f = \frac{1}{U_{\text{fouled}}} - \frac{1}{U_{\text{initial}}} \tag{2}$$

where U_{fouled} is the overall heat transfer coefficient for the fouled case, while U_{initial} is the overall heat transfer coefficient for the initial clean condition. These overall coefficients of heat transfer were calculated using Eq. (3):

$$Q = UA\Delta T_{\text{LMTD}} \tag{3}$$

where ΔT_{LMTD} (Eq. (4)) is the log mean temperature difference which was determined from measured temperature at the inlet and outlet of hot and solution water:

$$\Delta T_{\text{LMTD}} = \frac{(T_{\text{h,out}} - T_{\text{c,in}}) - (T_{\text{h,in}} - T_{\text{c,out}})}{\ln\left[\frac{(T_{\text{h,out}} - T_{\text{c,in}})}{(T_{\text{h,in}} - T_{\text{c,out}})}\right]} \tag{4}$$

It is noted that the heat transfer rate in the cooling water side was used to calculate the overall heat transfer coefficient. The solution was monitored every 2–5 h for the experiments with and without PWT, respectively. The deposited scale hardness of the solution was measured by the EDTA titration method.

3. Results and discussion

3.1. Calcium content in scale

Fig. 2 shows the results of analyses scale deposition of calcium sulphate on the metal surfaces. Calcium hardness was measured by titration method for both PWT and non-PWT cases at 300 mg L^{-1}. It can be observed that the system without PWT has higher hardness concentration compared to that with PWT. The highest calcium content is obtained at a low velocity of 0.3 m s^{-1} for both cases. These results show that the operation of the heat exchanger can be prolonged by reducing calcium sulphate scaling as in the PWT cases. The results are quite promising and indicate that the PWT method is capable of improving the efficiency and productivity of industries by reducing the breakdown frequency of the plant.

3.2. Fouling resistance

Fig. 3 shows the results for the fouling test obtained using water hardness of 300 mg L^{-1} and at different flow velocities (0.3–0.8 m s^{-1}) for PWT and non-PWT cases. The presence of a big amount of calcium ions in water, which reacted quickly to hot heat transfer surface should have been the cause in the rapid deposition in the early hour of the test, as indicated in the graph. In addition, we can observe that the fouling resistance is relatively low for all the case applied for all velocity when it is treated with PWT. Moreover, velocity of flow significantly affects the scale deposition. At 0.8 m s^{-1} flow velocity observed to have lower fouling resistance compared to 0.3 m s^{-1} suggesting that a significant removal of scale particles is taking place due to increase in shear stress on metal surface.

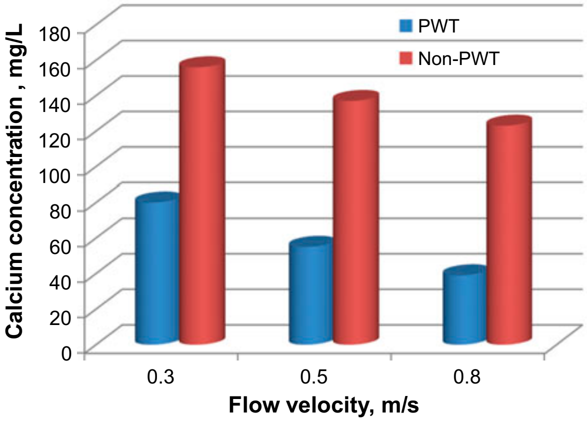

Fig. 2. Calcium content in scale.

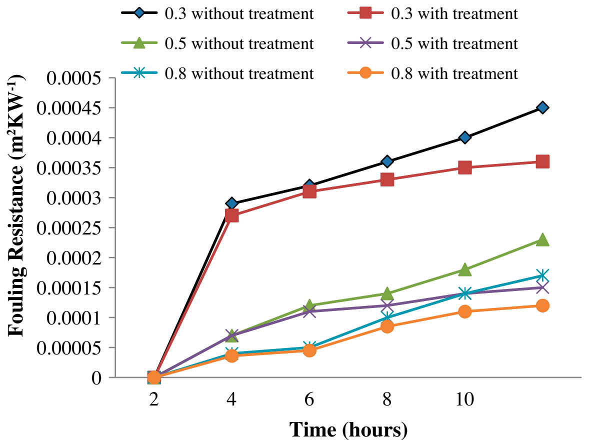

Fig. 3. Fouling resistance for PWT and non-PWT for different velocity.

3.3. Performance of catalytic materials in mitigating fouling problem

The results presented in Fig. 4 indicate that the performance of the device gradually decreases with respect to time. In this study, the initial water hardness was maintained at 300 mg L^{-1} and measurements of the water chemistry were carried out every 5 h in order to investigate the performance of the device. The experimental duration was 5 h and the initial concentration was maintained at 300 mg L^{-1} for each experimental run. The water hardness was measured by the EDTA complex metric titration method. An additional period of 75 h was required to perform one full cycle of testing to investigate the performance of the device.

A catalytic alloy surface was used to solve mineral fouling on the heat exchanger and determine its performance and efficiency. Several PWT methods have been implemented over the years, either in magnetic or electric fields.

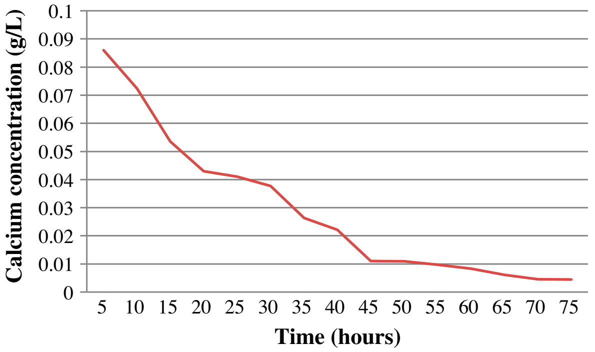

Fig. 4. Performance verification for catalytic material in fouling mitigation.

In addition, a few past studies suggested that the implementation of PWT on its own may be highly effective in solving fouling problems. Catalytic materials consisting of zinc and tourmaline are the focus of this study. Zinc is indeed an effective catalytic material while tourmaline is a polar crystalline material, which releases negative ions and is typically used in drinking water treatment processes. This study supports the idea that heterogeneous catalysis such as the PWT mechanism results in a significant reduction in mineral hardness without the need of magnetic and electric fields.

4. Conclusion

The results of this study show that the calcium carbonate hardness can be reduced by implementing PWT, whereby zinc and tourmaline are used as the catalytic materials. An experimental rig has been designed and fabricated specifically for the cooling water treatment experiments. The main conclusions drawn from this study are as follows:

(1) The calcium carbonate hardness reduces by 20–30% for cases with PWT compared to those without PWT. It is suggested that an increase in solution flow rate will prolong the lifespan of heat exchangers and cooling towers in industries.
(2) The performance of the device used in this study decreases gradually overtime, with a value of 5–8% over an interval of 5 h. This issue needs to be addressed in future work.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] D.J. Kukulka, M. Devgun, Fouling surface finish evaluation, Appl. Thermal Eng. 27(7) (2007) 1165–1172.
[2] T.R. Bott, Aspects of crystallization fouling, Exp. Therm. Fluid Sci. 14(4) (1997) 356–360.
[3] B. Bansal, X.D. Chen, H. Muller-Steinhagen, Analysis of ‘classical’ deposition rate law for crystallisation fouling, Chem. Eng. Process 47(8) (2008) 1201–1210.

[4] T.M. Paakkonen, M. Riihimaki, C.J. Simonson, E. Muurinen, R.L. Keiski, Crystallization fouling of $CaCO_3$—Analysis of experimental thermal resistance and its uncertainty, Int. J. Heat Mass Transfer 55(23–24) (2012) 6927–6937.

[5] H. Elfil, H. Roques, Prediction of the limit of the metastable zone in the "$CaCO_3$–CO_2–H_2O" system, AlCHE J. 50(8) (2004) 1908–1916.

[6] H. Muller-Steinhagen, M.R. Malayeri, A.P. Watkinson, Heat exchanger fouling: Mitigation and cleaning strategies, Heat Transfer Eng. 32(3–4) (2011) 189–196.

[7] T.R. Bott, Fouling of Heat Exchanger, Elsevier, Amsterdam, 1995.

[8] R. Steinhagen, H. Muller-Steinhagen, K. Maani, Problems and costs due to heat exchanger fouling in New Zealand industries, Heat Transfer Eng. 14(1) (1993) 19–30.

[9] S.A. Parsons, B.-L. Wang, S.J. Judd, T. Stephenson, Magnetic treatment of calcium carbonate scale—Effect of pH control, Water Res. 31(2) (1997) 339–342.

[10] G.J. Lee, L.D. Tijing, B.C. Pak, B.J. Baek, Y.I. Cho, Use of catalytic materials for the mitigation of mineral fouling, Int. Commun. Heat Mass 33(1) (2006) 14–23.

[11] L.D. Tijing, H.Y. Kim, D.H. Lee, C.S. Kim, Y.I. Cho, Physical water treatment using RF electric fields for the mitigation of $CaCO_3$ fouling in cooling water, Int. J. Heat Mass Transfer. 53(7–8) (2010) 1426–1437.

[12] S.N. Kazi, G.G. Duffy, X.D. Chen, Fouling mitigation of heat exchangers with natural fibres, Appl. Thermal Eng. 50(1) (2013) 1142–1148.

[13] M.A. Ashraf, M. Hussain, K. Mahmood, A. Wajid, M. Yusof, Y. Alias, I. Yusoff, Removal of acid yellow-17 dye from aqueous solution using eco-friendly biosorbent, Desalin. Water Treat. 51(22–24) (2013) 4530–4545.

[14] J. MacAdam, S. Parsons, Calcium carbonate scale formation and control, Rev. Environ. Sci. Biotechnol. 3(2) (2004) 159–169.

[15] C.Y. Tai, W.C. Chien, Interpreting the effects of operating variables on the induction period of $CaCl_2$–Na_2CO_3 system by a cluster coagulation model, Chem. Eng. Sci. 58(14) (2003) 3233–3241.

[16] Q. Yang, Y. Liu, A. Gu, J. Ding, Z. Shen, Investigation of induction period and morphology of $CaCO_3$ fouling on heated surface, Chem. Eng. Sci. 57(6) (2002) 921–931.

[17] M. Alahmad, Factors affecting scale formation in sea water environments—An experimental approach, Chem. Eng. Technol. 31(1) (2008) 149–156.

[18] D.J. Kukulka, M. Devgun, Fluid temperature and velocity effect on fouling, Appl. Thermal Eng. 27(16) (2007) 2732–2744.

[19] R.W. Morse, J.G. Knudsen, Effect of alkalinity on the scaling of simulated cooling tower water, Can. J. Chem. Eng. 55(3) (1977) 272–278.

[20] S.G.C.J.B. Thonon, Effect of geometry and flow conditions on particulate fouling in plate heat exchangers, Heat Transfer Eng. 20(3) (1999) 12–24.

[21] N.H. Hussin, I. Yusoff, Y. Alias, S. Mohamad, N.Y. Rahim, M.A. Ashraf, Ionic liquid as a medium to remove iron and other metal ions: A case study of the North Kelantan Aquifer, Malaysia, Environ. Earth Sci. 71(5) (2014) 2105–2113.