Applied Thermal Engineering 110 (2017) 495–503

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Retardation of heat exchanger surfaces mineral fouling by water-based diethylenetriamine pentaacetate-treated CNT nanofluids

K.H. Teng [a,b,*], Ahmad Amiri [c,*], S.N. Kazi [a,*], M.A. Bakar [a], B.T. Chew [a], A. Al-Shamma'a [b], A. Shaw [b]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] School of Built Environment, Liverpool John Moores University, Byron Street, Liverpool L3 3AF, United Kingdom
[c] Department of Chemical Engineering, Engineering Faculty, Ferdowsi University of Mashhad, Mashhad, Iran

HIGHLIGHTS

- Decoration EDTA on MWCNT surface to retard the rate of fouling.
- Preparation of DTPA-treated MWCNT/water nanofluid.
- Evaluating the mitigation of DTPA-treated MWCNT-based water nanofluids.
- Retarding of calcium carbonate crystals by MWCNT-DTPA additives.
- The effect of additive on the rate of fouling.

ARTICLE INFO

Article history:
Received 16 April 2016
Revised 8 July 2016
Accepted 27 August 2016
Available online 29 August 2016

Keywords:
Calcium carbonate
Crystallization fouling
Fouling mitigation
MWCNT-based water
DTPA

ABSTRACT

Mineral scale deposition on heat exchanging surfaces increases the thermal resistance and reduces the operating service life. The effect is usually intensified at higher temperatures due to the inverse temperature solubility characteristics of some minerals in the cooling water. Scale formation build up when dissolved salt crystallize from solution onto the heated surface, forming an adherent deposit. It is very important for heat transfer applications to cope with the fouling problems in industry. In this present study, a set of fouling experiments was conducted to evaluate the mitigation of calcium carbonate scaling by applying DTPA-treated MWCNT-based water nanofluids on heat exchanger surfaces. Investigation of additive DTPA-treated MWCNT-based water nanofluids (benign to the environment) on fouling rate of deposition was performed. 300 mg L^{-1} of artificially-hardened calcium carbonate solution was prepared as a fouling solution for deposit analysis. Assessment of the deposition of calcium carbonate on the heat exchanger surface with respect to the inhibition of crystal growth was conducted by Scanning Electron Microscope (SEM). The results showed that the formation of calcium carbonate crystals can be retarded significantly by adding MWCNT-DTPA additives as inhibition in the solution.

1. Introduction

The formation of scale deposits is a complex process, which involves besides the nucleation and growth the formation layer of particles that deposit through sendimentation of particles that either shortly after their formation or through collision adhere on the wall in contact with the aqueous fluids. This mechanism of scale formation, initiated and sustained by sedimentating particles is knows as "Fouling" [1–3]. Heat exchangers are an important part of industrial processes as they handle a major portion of total energy consumption. Water is the most common fluid used in these process and power industries. It is used as a cooling medium, as a process fluid, and even as a solvent. Many industries tent to locate where an easy access to water is available. The major sources of water include rivers, lakes, oceans, etc. However, because of water is a universal solvent, it dissolves everything it come to contact with including Ca^{2+} and Mg^{2+} and other mineral found in earth. When this water bond mineral are exposed to different physical influences, such as heat transfer, friction and pressure change, they can revert back into natural solid stage against with one another and always lead to the formation of deposits on the surfaces and causing fouling problems [4–6]. Therefore,

* Corresponding authors at: Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (K.H. Teng) and Department of Chemical Engineering, Engineering Faculty, Ferdowsi University of Mashhad, Mashhad, Iran (A. Amiri).
E-mail addresses: alex_teng1989@hotmail.com (K.H. Teng), ahm.amiri@gmail.com (A. Amiri), salimnewaz@um.edu.my (S.N. Kazi).

http://dx.doi.org/10.1016/j.applthermaleng.2016.08.181
1359-4311/

Nomenclature

W_s	weights of the deposited scale (g)
W_f	weights of the fouled coupon (g)
W_I	weights of the initial coupon (g)
R_f	fouling resistance (m^2 K/W)
U_{fouled}	overall heat transfer coefficient for the fouled case ($W\,m^{-2}\,K^{-1}$)
$U_{initial}$	overall heat transfer coefficient for the initial case ($W\,m^{-2}\,K^{-1}$)
Q	rate of heat gain (W)
A	total heat transfer surfaces (m^2)
ΔT_D	temperature difference which was determined from average temperature at the surface and bulk solution (K)
T_s	surface temperature (K)
T_B	bulk temperature (K)
M	solution mass flow rate (kg/s)
C_p	specific heat capacity constant ((kJ/(kg K))
T_o	outlet temperature (K)
T_i	inlet temperature (K)

many efforts have been made to solve this problem [7,8]. Scale deposition can form with the presence of sparingly salts such as $CaCO_3$, $CaSO_4$ and CaC_2O_4.

Scale is a solid layer attached to equipment surfaces and piping systems in which some materials, originally dissolved in fluids, are deposited on the surfaces under certain conditions. The formation of scale occurs during several industrial operations such as Crystallization, distillation, evaporation, mixing, cooling, or heating of liquids. The permanent scale formation results in serious industrial problems including reduced thermal efficiency of heat exchanger, induced under-deposit corrosion, increased pressure drop and upstream pressure in piping, cavitation and flow blockage [9]. The cost of scaling has been very high for industrial sector, which comprises various components such as special designs and construction of equipments, energy loss, maintenance costs and lost production [10,11]. At present, water fouling can be considered as a manageable problem, but at a high cost and usage of chemicals hazardous to environment. An environmental approach essential needed to overcome this fouling problem without use of hazardous chemicals. The research and development on fouling has progressed significantly in the last 15 years. The fouling mechanisms are now described in terms of processes associated with the formation, transportation, deposition, and removal mechanism. Major technical issues still remain before water fouling can be recognized as a solved problem [12].

There are four essential methodologies for $CaCO_3$ scale control: (a) support of low operational pH (b) utilization of sequestrates (c) upkeep of low cycles of focus, and (d) utilization of scale inhibitors [13]. Utilization of corrosive acid is a powerful approach to avoid calcium carbonate fouling development by keeping up a low pH. However, it raises worries because of its hazardous nature and the capability of accelerating metal erosion. The utilization of sequestering specialists is too excessive for open recycling water applications. Keeping up low cycles of focus prompts exorbitant waste water treatment in cutting edge. Scale inhibitor used is a generally acknowledged practice and includes expansion of moment measures of scale inhibitors in the recycling water [14]. These added substances contain phosphonate and/or carboxylate amasses, and can be monomeric or polymeric. They work at threshold levels, since the inhibitor concentration ratio is extremely high [15]. It is believed that they perform "threshold inhibition" by a surface adsorption mechanism involving Langmuir adsorption. Adsorption onto the $CaCO_3$ crystal surface(s) causes inhibition (or delay) of crystal growth at the very early stages. On the topic of scale inhibition mechanism, three possible inhibitor mechanism involved in scale inhibition were summarized by Liu et al. [16] as shown in Fig. 1.

Scale inhibitors are a group of chemical that are capable of reducing the rate of scale formation and precipitation. The function of scale inhibitors is to prevent the scale mineral crystal growth [17]. Application of scale inhibitors is by far the major scale control technique, the overall goal of the inhibitor treatment is to provide the longest possible protection against scale formation before another treatment is necessary [18]. As reported by Davey and Garside [19], the growth morphology can be affected by supersaturation, solvent, temperature and additives. The inhibitors can alter crystal surface properties and influence the electrical double layers causing change in nucleation, growth retardation, agglomeration, and morphology [20]. Each face of the crystal has a different surface lattice structure and a different distribution of adsorption sites. The additives absorb onto the crystal surface, changing the charge of surface and the associated electrical double layer, which in turn alters the dispersion properties. This varies the shape of the growing crystals [21]. The attractive features of these chemical additives such as ease of handling, relatively low cost, low dost rates, avoidance of corrosion problems arising from the use of mineral acids, and ability to impact on hard scale formation have made their use widespread [22].

Several chemical additives can be used to control scaling, but those that are used at present introduce hazards to the environment [23,24]. So investigators have tried to explore green additives, such as carboxyl methyl cellulose (CMC), cationic inulin polymer (cations), poly-allylamine hydrochloride (PALAM), and more environmentally benign additives [25]. A comprehensive study done by Hoang et al. [26] of nine organic additives which including EDTP, NTMP NDPA, HEDP, HEDP, NPDA, EDTA, NTA, citric acid and tartaric acid on the formation of calcium sulphate in a pipe system using a multiple flow system. The results revealed that low concentration of additives can retard the growth of calcium sulphate scale on the pipe walls.

Covalent modification has been suggested as a viable solution for developing interactivity [27,28]. In order to enhance the dispersibility of CNTs in pure water along with inhibiting the formation of large crystals, covalent functionalization by using diethylenetriamine pentaacetate (EDTA) proven a method for getting promising results [29]. From covalent alteration the crystal organisation is distorted, and the formation of large crystals is inhibited by the crystal modifying agents (e.g., polycarboxylic acid). The distorted crystals remain suspended in the bulk solution and do not settle on the heat transfer surface. However, particulate fouling may occur if their concentration increases beyond a certain limit. This is prevented either by using techniques to minimize particulate fouling or by using dispersing agents along with crystal-modifying agents. The resulting crystalline deposits are different from those formed in the absence of any additives. The layer can be removed easily as it loses its strength.

In the field of strong sorption, added substances are essentially vital for mitigate fouling on heat exchanger. Moderation of stores and improvement of heat exchange by incorporating additives are basic on a fundamental level [9]. The present work reports the impediment of fouling rates on heat exchanger surfaces in the vicinity of a biodegradable added substance (MWCNT-DTPA). This