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Industrial Heat Exchanger: Operation and Maintenance to Minimize Fouling and Corrosion

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Additional information is available at the end of the chapter

Abstract

Heat exchanger is equipment used to transfer heat from one fluid to another. It has extensive domestic and industrial applications. Extensive technical literature is available on heat exchanger design, operation and maintenance, but it is widely scattered throughout the industrial bulletins, industrial design codes and standard, technical journals, etc. The purpose of this book chapter is to consolidate into basic background and concepts design of heat exchangers, operation, cleaning and green technology maintenance on heat exchanger closely related to the industrial practices.

Keywords: heat exchanger, fouling, fouling mitigation, green technology, cleaning of heat exchangers

1. Introduction

Heat exchanger plays an important role in industrial application. It is implemented for the purposes of heating and cooling of large-scale industrial process fluids [1]. Heat exchanger is a dynamic design which can be customized to suit any industrial process depending on the temperature, pressure, type of fluid, phase flow, density, chemical composition, viscosity and many other thermodynamic properties [2, 3]. Due to global energy crisis, an efficient heat recovery or dissipation of heat has become a vital challenge for Scientists and Engineers [4].

Heat exchangers are designed to optimize the surface area of the wall between two fluids to maximize the efficiency, while minimizing resistance to fluid flow through the exchangers within constrain of material cost. The performance of heat exchanging surfaces could be enhanced by the addition of corrugations or fins in heat exchanger, which increase surface area and may channel fluid flow or induce turbulence [5]. Efficiency of industrial heat exchangers could be online monitored by tracking the overall heat transfer coefficient based on its temperatures which tends to decline over time due to fouling [6].

Potential damage towards equipment caused by formation of scale can be very costly if processed water is not treated correctly. Chemicals are commonly used to treat the water in the industry. A total of 7.3 billion dollar worth chemicals per year in the U.S. is released into the air, dumped in streams and buried in landfills every year. Forty percent of these chemicals is purchased by industry for control of scale in cooling tower, boiler and other heat transfer equipment. This percentage also represents more than 2 billion dollar of toxic waste which contribute to trillion of gallon contaminated water disposed annually into the earth which belongs to all of us.

Maintenance of fouled tubular heat exchangers can be performed by several methods such as acid cleaning, sandblasting, high-pressure water jet, bullet cleaning or drill rods. In large-scale cooling water systems for heat exchangers, water treatment such as purification, addition of chemicals, catalytic approach, etc., are used to minimize fouling of the heat exchanging equipment [7]. Other water treatment processes are also used in steam systems for power plants to minimize fouling and corrosion of the heat exchanger and other equipment. Most of the chemical and additives used for fouling and corrosion mitigation are hazardous to the environment [8]. So, the days have come to apply chemicals of approaches benign to the environment [9–11].

2. About industrial heat exchanger

An industrial heat exchanger is heat transfer equipment that utilizes a thermal energy exchange process between two or more medium available at different temperature. Industrial heat exchangers are applied in various industrial applications such as power plant generation, petroleum oil and gas industry, chemical processing plant, transportation, alternate fuels, cryogenic, air conditioning and refrigeration, heat recovery and other industries. In addition, heat exchangers are the equipment always closely related to our daily life, for example, evaporators, air preheaters, automobile radiators, condensers and oil coolers. In most heat exchangers, a heat transfer surface separates the fluid which incorporates a wide range of different flow configuration to achieve the desired performance in different applications. Heat exchangers could be classified in many different ways. Generally, industrial heat exchangers have been classified according to construction, transfer processes, degrees of surface compactness, flow arrangements, pass arrangements, phase of the process fluids and heat transfer mechanisms as seen in **Figure 1**.

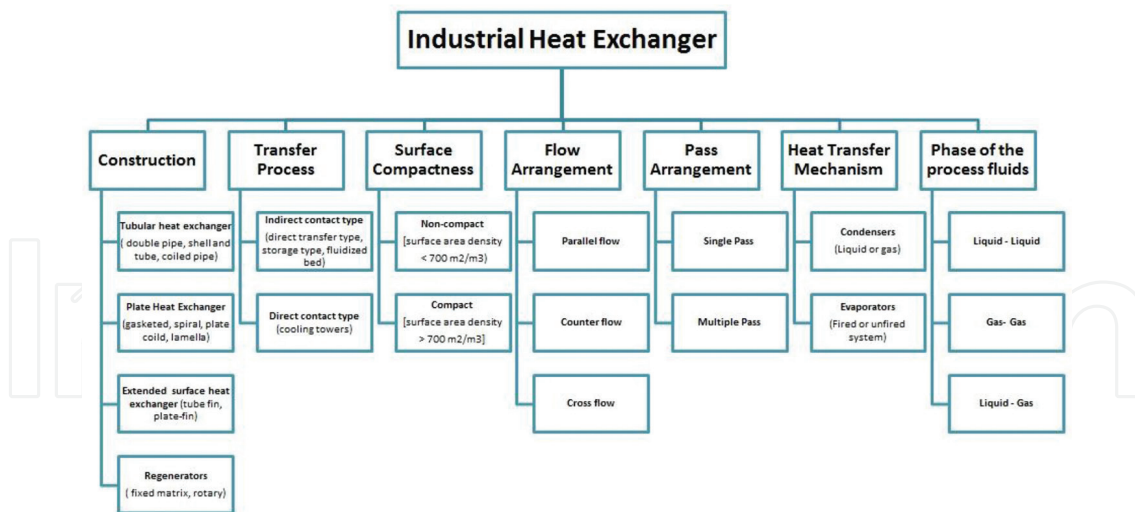


Figure 1. Classification of industrial heat exchanger [12].

3. Basic design concepts for heat exchanger

The design concepts of heat exchanger must meet normal process requirements specified through service conditions for combinations of un-corroded and corroded conditions and the clean and fouled conditions. One of the critical criteria of heat exchanger design is the exchanger must be designed for ease of maintenance, which usually means cleaning or replacement of parts, tubing, fittings, etc. damaged by ageing, vibration, corrosion or erosion throughout the service period.

Hence, a heat exchanger design should be as simple as possible particularly if heavy fouling is expected. By minimize temperature in conjunction with the choice of fluid velocity and reducing the concentration of foulant precursors, will reduce the incidence of potential fouling. Moreover, highest flowing velocity should be allowed under the constraints of pressure drop and erosion from the flow. In addition, material selection within constrained cost retards the build-up of deposits and allows shorter residence time. It should also be compatible in terms of pH, corrosion and not only just heat exchanger, but also in terms of heat equipment and transfer lines of the heat exchanger.

4. Fouling

Fouling is always defined as the formation and accumulation of unwanted materials deposit onto the processing equipment surfaces. These normally very low thermal conductivity materials form an insulation on the surface which can extremely deteriorate the performance of the surface to transfer heat under the temperature difference for which it was designed [13]. On top of this, fouling increases the resistance to fluid flow, resulting in higher pressure drop

across the heat exchanger. Many types of fouling can occur on the heat transfer surfaces, for examples, crystallization fouling, particulate fouling, corrosion fouling, chemical reaction fouling, biological fouling and solidification fouling [14]. Fouling can have a very costly effect in the industries which eventually increases fuel usage, interrupts operation, production losses and enhances maintenance costs [15].

The fouling is formed in five stages which can be summarized as initiation of fouling, transport to the surface, attachment to the surface, removal from the surface and ageing at the surface [16]. There are a few parameters influencing the fouling factors, such as pH [9], velocity [17], bulk temperature of fluid [18], temperature of the heat transfer surface, surface structure [19] and roughness [20, 21].

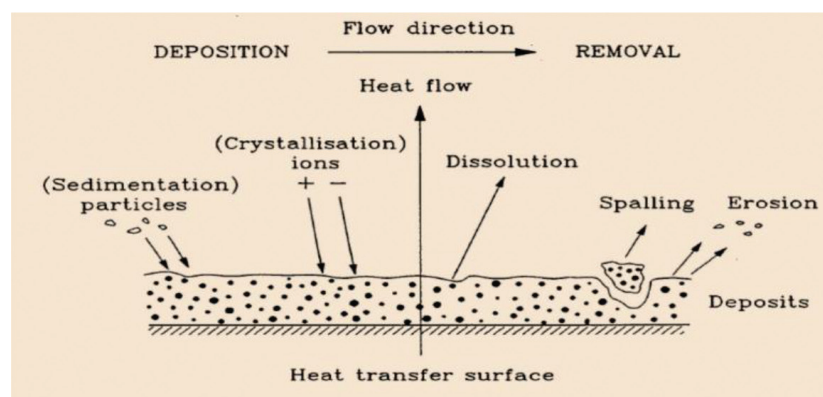


Figure 2. Overall fouling process [22].

The overall fouling process is usually considered to be the net result of two simultaneous sub processes: a deposition process and a removal process as shown in **Figure 2**. As illustrated in

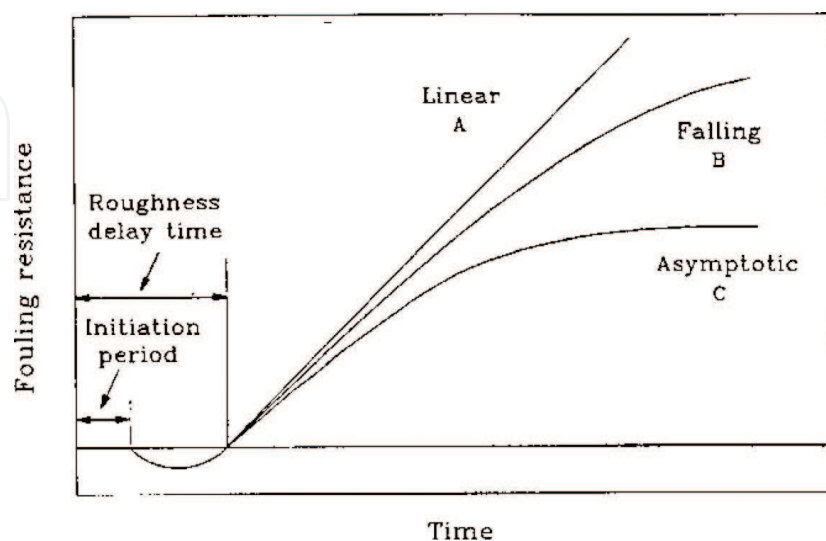


Figure 3. Fouling resistance against time curves [22].

Figure 3, the growth of these deposits causes the heat transfer performance of heat exchanger to decline with time. This problem affects the energy consumption of industrial processes and eventually causes industrial breakdown due to the heat exchanger failure as seen in **Figure 4**.



Figure 4. Heavy build-up of deposition on heat exchanger piping [24, 23].

5. Corrosion

Environment features such as soil, atmosphere, water or aqueous solutions commonly attack general metal and alloys. The deterioration of these metals is known as corrosion. It is agreeable that corrosion happens due to electrochemical mechanism. Premature failures in various equipment are caused by corrosion in most commercial processes and engineering operations, leading to unwanted issues. This includes pricey breakdown, un-schedule shutdown and increases in maintenance cost.

This downtime worsens in fields such as chemical industries, oil refining, sea and land electric power plant, paper manufacture, air conditioning, refrigerator, food and liquor manufacturing. Hence, general info and mechanism of corrosion will bring great interest to public and

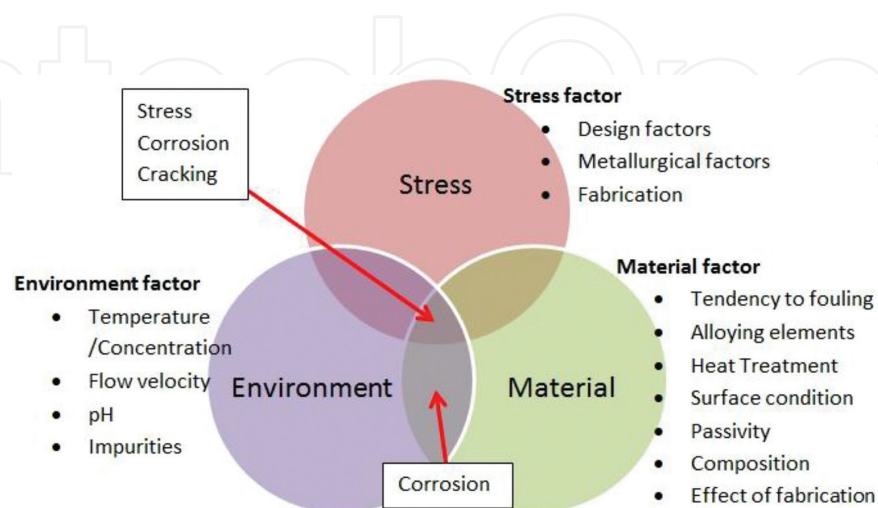


Figure 5. Factor influencing corrosion [25].

industry [24]. The corrosion process is affected by various parameters as show in **Figure 5**. Hence, these criteria should take consideration into the design basics of heat exchangers.

6. Cost imposed due to fouling

Apart from the high cost of heat exchanger fouling, very few work have been reported to accurate determine economic penalties causes by fouling. Therefore, these attribute cost to difference aspect of heat exchanger design and operation. However, reliable knowledge of fouling economics is desirable in order to evaluate the cost efficiency of various mitigation strategies [26, 27]. The total fouling-related costs involve the following:

1. Capital expenditure

Excessive surface area required to overcome the heavy fouling conditions, costs for stronger foundation, provision for extra spaces and increased transportation and installation costs.

2. Energy costs

Costs for extra fuel required if fouling leads to extra fuel burning in heat exchanging equipment to overcome the effect of fouling.

3. Maintenance costs

Costs for removal of fouling deposits, costs for chemicals or other operating costs for anti-fouling devices.

4. Cost of production loss

Planned or unplanned plant shutdowns due to fouling in heat exchangers can cause large production losses. These losses are often considered to be the main cost of fouling and very difficult to estimate.

5. Extra environmental management cost

Cost for disposing large amount of chemical/additives used for fouling mitigation.

Country	Fouling cost US \$ million	GNP (1984) US \$ billion	Fouling costs % of GNP
USA	3860–7000 8000–10,000	3634	0.12–0.22 0.28–0.35
Japan	3062	1225	0.25
West Germany	1533	613	0.25
UK	700–930	285	0.20–0.33
Australia	260	173	0.15
New Zealand	35	23	0.15
Total industrial world	26,850	13,429	0.20

Table 1. Estimated fouling costs incurred in some countries (1992 estimation) [28].

Huge fouling costs are reported in different countries. Steinhagen et al. reported about the fouling costs in term of GNPs for some countries as presented in **Table 1**.

7. Current efforts to solve fouling deposition and corrosion problems

A lot of works have been done to reduce fouling formation and control of corrosion. In recent years, numerous methods have been developed to control fouling and corrosion [29]. These methods can be classified as chemical means (inhibitor), mechanical means, changing the phases of the solution, electromagnetic fields, electrostatic fields, acoustic fields, ultraviolet light, radiation or catalytic treatment, surface treatment, green additives, fibre as a suspension, etc. In the past, chromate was a successful chemical agent for corrosion protection and crystal growth control until it was banned. Polyphosphate corrosion inhibitor was introduced for the replacement for chromate-based additives. This inhibitor has a tendency to decompose the foulant in water containing high calcium hardness. Knudsen et al. investigated fouling of high calcium water containing phosphate corrosion inhibitor. Four different copolymers were used to inhibit the deposition of calcium phosphate which includes acrylic acid/maleic anhydride (AA/MA), acrylic acid/hydroxypropyl acrylate (AA/HPA), acrylic acid/sulfonic acid (AA/SA) and sulfonated styrene/maleic anhydride (SS/MA). Studies were carried out by varying the pH, surface temperature and velocities. The investigation reported stated that AA/HPA and (AA/SA) were both very effective in inhibiting deposition of calcium phosphate and corrosion.

On the other hand, catalyst material composed of zinc and tourmaline was studied to mitigate fouling and corrosion. Tijing et al. reported that catalyst material potentially reduces calcium carbonate fouling formation [30]. Teng et al. reported the similar finding of catalyst material on calcium sulphate mitigation [31]. Moreover, Tijing et al. further extended the research by using same catalyst material to mitigate corrosion on carbon steel piping [31].

In the past, most of the methods used, chemical/additives for fouling and corrosion mitigation are hazardous to the environment. So, the days have come to apply green technology method and chemicals approaches benign to the environment [9–11].

8. Fouling mitigation by green technology (catalytic mitigation and green additive)

Physical water treatment (PWT) is a good alternative for safe and efficient nonchemical fouling mitigation method. Examples of PWT include permanent magnets [32], solenoid coil devices [33], green additive [34] and catalytic materials and alloys [35].

To mitigate scaling on heat transfer surfaces, chemical additives are often used, but chemicals are expensive and pose hazard threat to the environment and health. Mitigation of calcium sulphate dehydrates scale formation on heat exchanger surfaces by using natural wood pulp fibre was conducted by Kazi [36] and others in University of Malaya. Experimental work was

designed and fabricated to study the use of natural wood pulp fibre as a means of fouling mitigation as seen in **Table 2** and **Figure 6**.


Experimental test rig	
Experimental condition	Fluid velocity = 0.1 m/s Bulk temperature = 30°C Δ Temperature = 15°C CaSO_4 = 3.6 g/l C_{fibre} = 0.005–0.1%
Green additive	Bleached kraft pup fibre -Freeness–720 CSF -Average length–2.51 mm -Coarseness–0.224
Test specimen materials	SS316, brass, copper, aluminium

Table 2. Experiments set-up for fouling mitigation by incorporating green additives [36, 37].

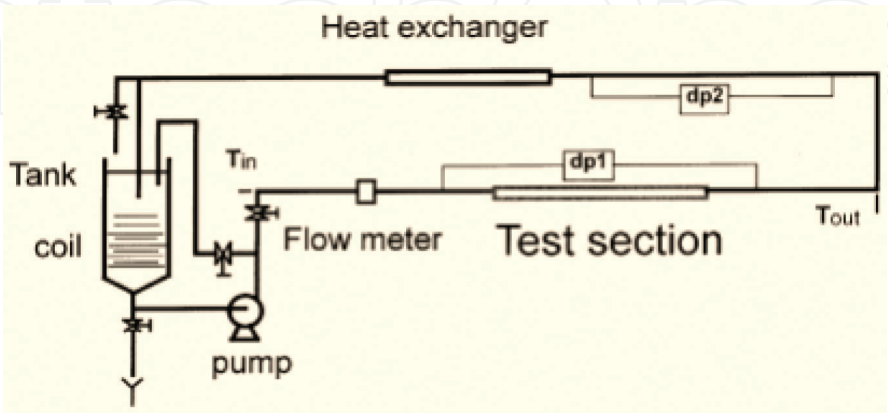


Figure 6. Schematic diagram of experiemental flow loop [37, 36].

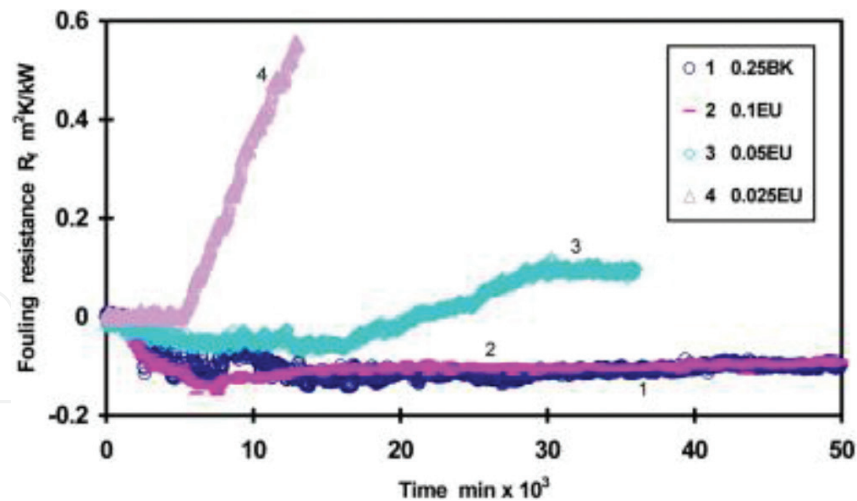


Figure 7. Fouling resistance as a function of time for eucalyptus fibre in the supersaturated calcium sulphate solution [38, 37].

Figure 7 depicts the fouling resistance as a function of time for calcium sulphate solution with different fibre concentration of 0.25% (1), 0.15% (2), 0.05% (3) and 0.02% curve (4) in the mineral solution. Results show that the fibres in solution retarded fouling on heated surfaces and the retardation is proportional to the concentration of fibre in the solution. The induction period has also increased.

9. Cleaning of heat exchanger

In order to maintain or restore efficiency of the heat exchanger, it is often necessary to clean the heat exchangers. Methods of cleaning may be classified into two groups: online and offline cleaning [38]. In some applications, the cleaning can be done online to maintain acceptable performance without interruption of operation. In other cases, offline cleaning must be used.

9.1. Online cleaning

Online cleaning generally utilizes a mechanical method designed for only tube side and requires no disassembly. The advantages of online cleaning are the continuity of service of the heat exchanger with the hope that no cleaning-mandated downtime will occur. However, it adds extra cost of a new heat exchanger installation or the large cost of retrofits and there is no assurance that all the tubes would be cleaned sufficiently.

I. Circulation of sponge rubber balls [39]

The technique is capable of preventing the accumulation of particulate matter, biofilm formation and scale and corrosion product deposition. It is only applicable to flow through the inside of tubes.

II. Two phases of the ferrous sulphate treatment

The first phase involves the initial laying down of the protective film. The second phase involves the maintenance of the film, which would be otherwise destroyed by the shear effects of flow.

III. Chlorination used for combat bio-fouling [40]**IV. Scale inhibitors [10, 41, 42]****V. Magnetic devices [10, 43, 44]****VI. Sonic technology [45]**

High and low frequency sound emitters (horns) are used to relief fouling problems on heat exchangers. The use of sound is much less effective in sticky and tenacious deposits that are generally associated with slagging.

VII. Online chemical cleaning [46]

Injection of chemical solutions into the process streams for the cleaning purposes.

VIII. The use of radiation [47]

Radiation sterilization of microbial-laden water, the use of ultraviolet light and Gamma rays have been considered for a long time.

9.2. Offline cleaning

An alternative to online cleaning is to stop operation and clean the heat exchanger. Offline cleaning can be classified into offline chemically cleaning or by mechanical means. The cleaning method preferred without the need to dismantle the heat exchangers, but usually it is necessary to have access to the inside surfaces. It would be prudent to consider the installation of a “standby” heat exchanger, thereby providing the opportunity to clean the fouled heat exchanger while at the same time maintain the production.

9.2.1. Offline mechanical cleaning**a. Tube drilling and rodding [28]**

Devices may be applied to the rotating shaft including drills, cutting and buffing tools and brushes that may be made from different materials, for example, steels or nylon, brasses depending on the tube material and the nature of the deposit.

b. Cleaning with explosives

Used of controlled explosions, where the energy to remove the deposits, is transmitted by a shock wave in the air adjacent to the surface to be cleaned or by the general vibration of tubes brought about the explosion. It is a relatively new innovation introduced in boiler plant cleaning. It is possible to begin the cleaning process, while the structure is still hot.

c. Thermal shock [48]

Changes in temperature particularly rapid changes, cause cracking of foulant layer with the possibility of flaking. This technique is similar to steam soaking. The water flushing carries away the dislodged material and it is repeated until clean surfaces are obtained.

9.2.2. *Offline chemical cleaning*

- a. Inhibitor hydrofluoric, hydrochloric, citric, sulphuric acid or EDTA (chemical cleaning agent) for iron oxides, calcium/magnesium scales (foulant), etc. cleaning [49].

Inhibitor hydrofluoric acid is by far the most effective agent but cannot be used if deposits contain more than 1% w/v calcium.

- b. Chlorinated or aromatic solvents followed by washing are suitable for heavy organic deposits for example, tars and polymers (foulant) [50].
- c. Alkaline solutions of potassium permanganate [51] or steam-air decoking [52] are suitable for cleaning carbon (foulant) deposition.

10. Conclusion

Fouling and corrosion are the major unresolved crisis in heat exchanger operation. Though the fouling deposition problems and the impact to the economy are a serious concern, still there is lack of awareness in concerned authorities. In addition, the penalties of corrosion are numerous and varied and the effects of these on the efficient, reliable and safe operation of equipment or structures are often more serious than the simple loss of a mass of metal. Therefore, the present paper will promote concerned organization in different countries, seriousness of this problem and application of possible mitigation approach.

For an industry, the proper cleaning method and control play important role to reduce the production costs. Production cost significantly increases due to chemical usage, maintenance work and downtime loss and water wastage. Consequently, the related authorities need to comprehend the importance of corrosion control, fouling cleaning and enforce a specific standard of cleaning procedure in the industries.

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References

- [1] Bott, T.R., *CHAPTER 1 - Introduction, in Fouling of Heat Exchangers*. 1995, Elsevier Science B.V.: Amsterdam. p. 1–6.
- [2] Alahmad, M., *Factors affecting scale formation in sea water environments—an experimental approach*. Chemical Engineering and Technology, 2008. 31(1): pp. 149–156.
- [3] Bott, T.R., *Aspects of crystallization fouling*. Experimental Thermal and Fluid Science, 1997. 14(4): pp. 356–360.
- [4] Somerscales, E.F.C., *Fouling of Heat Transfer Equipment*. Hemisphere, New York, 1981.
- [5] Epstein, N., *Heat Exchanger Theory and Practice*. In Heat exchangers, J. Taborek and G. Hewitt (Eds.), 1983. In Heat Exchanger Theory and Practice: McGraw-Hill.
- [6] Panchal, C.B. and J.G. Knudsen, *Mitigation of Water Fouling: Technology Status and Challenges*, In *Advances in Heat Transfer*, T.F.I.Y.I.C. James P. Hartnett and A.G. George, Editors. 1998, Elsevier. pp. 431–474.
- [7] Kazi, S.N., et al., *Study of mineral fouling mitigation on heat exchanger surface*. Desalination, 2015. 367: pp. 248–254.
- [8] Karagiannis, I.C. and P.G. Soldatos, *Water desalination cost literature: review and assessment*. Desalination, 2008. 223(1–3): pp. 448–456.
- [9] MacAdam, J. and S.A. Parsons, *Calcium carbonate scale formation and control*. Re/Views in Environmental Science and Bio/Technology, 2004. 3(2): pp. 159–169.
- [10] Macadam, J. and S. Parsons, *Calcium carbonate scale control, effect of material and inhibitors*. Water Science and Technology, 2004. 49(2): pp. 153–159.
- [11] Kazi, S.N., G.G. Duffy and X.D. Chen, *Fouling and fouling mitigation on heated metal surfaces*. Desalination, 2012. 288: pp. 126–134.

- [12] Thulukkanam, K., *Heat Exchangers*, in *Heat Exchanger Design Handbook, Second Edition*. 2013, CRC Press: United Kingdom. p. 1–38.
- [13] Hans, M.-S., *C4 Fouling of Heat Exchanger Surfaces*, in *VDI Heat Atlas*. 2010, Springer Berlin Heidelberg. pp. 79–104.
- [14] Bott, T.R., *Fouling in Heat Transfer Equipment*. The Chemical Engineering, 1971: pp. 391–395.
- [15] Steinhagen, R., H. Müller-Steinhagen and K. Maani, *Problems and costs due to heat exchanger fouling in New Zealand industries*. Heat Transfer Engineering, 1993. 14(1): pp. 19–30.
- [16] Mullin, J.W., *Crystallisation*. 4th ed. 2001, London, UK: Butterworth-Heineman.
- [17] Kukulka, D.J. and M. Devgun, *Fluid temperature and velocity effect on fouling*. Applied Thermal Engineering, 2007. 27(16): pp. 2732–2744.
- [18] Hoang, T.A., H.M. Ang and A.L. Rohl, *Effects of temperature on the scaling of calcium sulphate in pipes*. Powder Technology, 2007. 179(1): pp. 31–37.
- [19] Razmjou, A., J. Mansouri and V. Chen, *The effects of mechanical and chemical modification of TiO₂ nanoparticles on the surface chemistry, structure and fouling performance of PES ultrafiltration membranes*. Journal of Membrane Science, 2011. 378(1): pp. 73–84.
- [20] Kazi, S.N., G.G. Duffy and X.D. Chen, *Mineral scale formation and mitigation on metals and a polymeric heat exchanger surface*. Applied Thermal Engineering, 2010. 30(14–15): pp. 2236–2242.
- [21] Albert, F., W. Augustin and S. Scholl, *Roughness and constriction effects on heat transfer in crystallization fouling*. Chemical Engineering Science, 2011. 66(3): pp. 499–509.
- [22] Mostafa M. Awad (2011). Fouling of Heat Transfer Surfaces, Heat Transfer – Theoretical Analysis, Experimental Investigations and Industrial Systems, Prof. Aziz Belmiloudi (Ed.), InTech, DOI: 10.5772/13696. Available from: <http://www.intechopen.com/books/heat-transfer-theoretical-analysis-experimental-investigations-and-industrial-systems/fouling-of-heat-transfer-surfaces>
- [23] S. N. Kazi (2012). Fouling and Fouling Mitigation on Heat Exchanger Surfaces, Heat Exchangers – Basics Design Applications, Dr. Jovan Mitrovic (Ed.), InTech, DOI: 10.5772/32990. Available from: <http://www.intechopen.com/books/heat-exchangers-basics-design-application/heat-exchanger-fouling-and-its-mitigation>
- [24] Åse Dragland and Sverre G. Johnsen (2010). Vil til bunns i begroingsproblemene, Teknisk Ukeblad, Sept. 2010. Available from: <https://www.tu.no/artikler/industri-vil-til-bunns-i-begroingsproblemene/250792>
- [25] Thulukkanam, K., Corrosion, in *Heat Exchanger Design Handbook, Second Edition*. 2013, CRC Press: United Kingdom. p. 665–748.

- [26] Teng, K.H., et al., *Retardation of heat exchanger surfaces mineral fouling by water-based diethylenetriamine pentaacetate-treated CNT nanofluids*. Applied Thermal Engineering, 2017. 110: pp. 495–503.
- [27] Teng, K.H., et al., *Fouling mitigation on heat exchanger surfaces by EDTA-treated MWCNT-based water nanofluids*. Journal of the Taiwan Institute of Chemical Engineers, 2016. 60: pp. 445–452.
- [28] Müller-Steinhagen, H., M. Malayeri and A. Watkinson, *Heat exchanger fouling: mitigation and cleaning strategies*. Heat Transfer Engineering, 2011. 32(3–4): pp. 189–196.
- [29] Alahmad, M., *Experimental study of scale formation in sea water environment*. Journal of King Saud University, 2004. 17(1): pp. 73–88.
- [30] Tijging, L.D., et al., *Mitigation of scaling in heat exchangers by physical water treatment using zinc and tourmaline*. Applied Thermal Engineering, 2011. 31(11): pp. 2025–2031.
- [31] Teng, K., et al., *Mitigation of heat exchanger fouling in industry using catalytic materials*. Desalination and Water Treatment, 2016. 57(1): pp. 22–27.
- [32] Lee, G.J., et al., *Use of catalytic materials for the mitigation of mineral fouling*. International Communications in Heat and Mass Transfer, 2006. 33(1): pp. 14–23.
- [33] Tijging, L.D., et al., *Physical Water Treatment Using Oscillating Electric Fields to Mitigate Scaling in Heat Exchangers*, in *Frontiers and Progress in Multiphase Flow I*. 2014, Springer. p. 105–155.
- [34] Hasson, D., H. Shemer and A. Sher, *State of the art of friendly “green” scale control inhibitors: a review article*. Industrial and Engineering Chemistry Research, 2011. 50(12): pp. 7601–7607.
- [35] Brinis, H. and M.E.H. Samar, *A method for inhibiting scale formation and corrosion in a cooling water system*. Desalination and Water Treatment, 2013. 52(13–15): pp. 2609–2619.
- [36] Kazi, S.N., G.G. Duffy and X.D. Chen, *Fouling mitigation of heat exchangers with natural fibres*. Applied Thermal Engineering, 2013. 50(1): pp. 1142–1148.
- [37] Kazi, S.N., G.G. Duffy and X.D. Chen, *Fiber-modified scaling in heat transfer fouling mitigation*. Chemical Engineering Communications, 2002. 189(6): pp. 742–758.
- [38] Müller-Steinhagen, H., M.R. Malayeri and A.P. Watkinson, *Fouling of heat exchangers—new approaches to solve an old problem*. Heat Transfer Engineering, 2005. 26(1): pp. 1–4.
- [39] H. Müller-Steinhagen, M. R. Malayeri, A. P. Watkinson. (2011) Heat Exchanger Fouling: Mitigation and Cleaning Strategies. Heat Transfer Engineering 32:3–4, pages 189–196.
- [40] Rajagopal, S., et al., *How effective is intermittent chlorination to control adult mussel fouling in cooling water systems?* Water Research, 2003. 37(2): pp. 329–338.

- [41] Choi, D.-J., S.-J. You and J.-G. Kim, *Development of an environmentally safe corrosion, scale and microorganism inhibitor for open recirculating cooling systems*. Materials Science and Engineering: A, 2002. 335(1–2): pp. 228–235.
- [42] Lin, Y.-P. and P.C. Singer, *Inhibition of calcite crystal growth by polyphosphates*. Water Research, 2005. 39(19): pp. 4835–4843.
- [43] Parson, S.A., et al., *Magnetically augmented water treatment*. Process Safety and Environmental Protection, 1997. Transaction of the Institution of Chemical Engineering 75(Part B): pp. 98–104.
- [44] Parsons, S.A., et al., *Magnetic treatment of calcium carbonate scale—effect of pH control*. Water Research, 1997. 31(2): pp. 339–342.
- [45] Lin, S. and X. Chen, *A laboratory investigation of milk fouling under the influence of ultrasound*. Food and Bioproducts Processing, 2007. 85(1): pp. 57–62.
- [46] Chen, X.D., et al., *On-line fouling/cleaning detection by measuring electric resistance—equipment development and application to milk fouling detection and chemical cleaning monitoring*. Journal of Food Engineering, 2004. 61(2): pp. 181–189.
- [47] Park, J.-S., et al., *Fouling mitigation of anion exchange membrane by zeta potential control*. Journal of Colloid and Interface Science, 2003. 259(2): pp. 293–300.
- [48] Wilson, D., *Challenges in cleaning: recent developments and future prospects*. Heat Transfer Engineering, 2005. 26(1): pp. 51–59.
- [49] Madaeni, S. and S. Samieirad, *Chemical cleaning of reverse osmosis membrane fouled by wastewater*. Desalination, 2010. 257(1): pp. 80–86.
- [50] Arhancet, G.B., *Compositions and methods for inhibiting fouling of vinyl monomers*. 1999, Google Patents.
- [51] Spicher, R.G. and R.T. Skrinde, *Potassium permanganate oxidation of organic contaminants in water supplies*. Journal American Water Works Association, 1963: pp. 1174–1194.
- [52] Clavenna, L., et al., *Method for reducing fouling in a refinery*. 2006, Google Patents.

