Environmental and Economic Impacts of Biofouling on Marine and Coastal Heat Exchangers

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Chapter 25
Environmental and Economic Impacts of Biofouling on Marine and Coastal Heat Exchangers

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Abstract Biofouling is a major problem that affects the heat transfer efficiency of marine and coastal heat exchangers. The reduced heat exchanger efficiency results in energy loss and thereby affects the overall energy efficiency in the marine industry segment. Additional energy is required to compensate for the energy loss leading to increased fuel consumption which in turn contributes to global environmental issues like climate change. The current industrial methods of biofouling mitigation or removal from heat exchanger surfaces increase both operational and maintenance expenditure causing further environmental damages. This paper presents two models to provide an overview of the major environmental and economic impacts due to biofouling in marine heat exchangers. The study results suggest the need for sustainable biofouling prevention techniques to improve the energy and resource efficiency of marine heat exchangers.

Keywords Biofouling · Heat exchanger · Energy efficiency · Resource efficiency · Environmental impacts

25.1 Introduction

In the twenty-first century, society faces a lot of environmental issues. Of particular concern is the climate-related issues which are predominantly caused by industrialization. Industrial development has made our lives more comfortable, but it has also caused a huge demand in the energy requirement. For the past century, this energy demand has been mainly satisfied through the combustion of fossil fuels,

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which resulted in the increased emission of greenhouse gases. This has led to global warming and climate change. The effects of climate change are already visible in the form of floods, hurricanes, drought, heatwaves, melting of polar icescapes, and rise in the seawater levels, among others (Bott 2006). On the other hand, with the current technology improvements, it is evident that the demand for energy will not decline but will be increasing every year. Therefore, it is important to improve the energy efficiency of our industrial processes to reduce the environmental impact.

The marine industry segment has a lot of industrial processes associated with energy transfer. It is significant to have energy efficient devices in these processes. Heat exchangers are widely used for heat transfer or energy transfer applications in the marine industry. Marine heat exchangers are mainly installed and operated in offshore industries like oil refineries, desalination plants, power generation and chemical plants (Malayeri et al. 2015). The efficiency loss in these heat exchanger devices will thereby have a significant effect on the energy utilization in the marine industry segment.

Biofouling of marine heat exchangers is an issue faced by offshore industries all over the world. In the marine industry, biofouling could be described as the undesirable accumulation of deposits (biotic) on equipment surfaces by adhesion, growth and reproduction (Cao et al. 2011; Callow and Callow 2011). Marine biofouling on heat exchangers can be classified into microfouling (fouling due to microscopic organisms like bacteria and diatoms) or macrofouling (fouling due to macroorganisms like barnacles, oysters, mussels, polychaete worms, bryozoans and seaweed) (Cao et al. 2011; Callow and Callow 2011). Biofouling is generally more severe in areas where the water temperature is high because it provides the ideal condition for breeding and growth of biofouling organisms (Ratel et al. 2013). The intensity of marine biofouling in heat exchanger surface depends on several factors like the process fluid, exchange type and geometry, operating conditions, among others (Ratel et al. 2013).

The high importance of the heat exchanger equipment in the marine industrial applications intensify the criticality of the biofouling problem. Biofouling mainly affects the heat transfer efficiency of the heat exchanger equipment, which leads to energy loss (Hansen 2018). This additional energy requirement is mostly fulfilled by fossil fuel combustion and contributes to more emission of greenhouse gases (Bott 2006). Numerous studies have estimated that heat exchanger fouling leads to additional costs in the order of 0.25% of the gross domestic product (GDP) of industrialized countries (Malayeri et al. 2015; Müller-Steinhagen et al. 2011). Thus the biofouling of heat exchangers not only compromises the environmental welfare but also leads to significant economic losses (Costa et al. 2011).

25.2 Methodology

In this paper, a research study is conducted to find out the main environmental and economic impacts due to biofouling in marine and coastal heat exchangers. The research study was performed as part of the joint project between the Chalmers University of Technology, JOIN Business & Technology AB, Electrical Pipe for Fluid Transport AB (EPFF), and Alfa Laval Corporate AB. The study consisted of a literature review and interviews with different stakeholders in the project. Quantitative assessments of the environmental and economic impacts were not included in the study.

The material for the literature study was gathered by using databases like Scopus, Science Direct, Web of Science, and Google Scholar. The literature mainly consists of papers from both journals and conferences. There was no specific year limit used in the selection process. For a quick determination of whether a paper is relevant for the study or not, title, abstract, introduction, and conclusion were studied. To find more interesting publications, references of references were tracked. All the quantitative information provided in the report has been gathered from various articles used in the literature study.

Semi-structured interviews were conducted with heat exchanger product experts. The interviews helped to understand the problems associated with biofouling prevention from an economic perspective as well as from an environmental perspective. A qualitative analysis of the information gathered from both the literature study and the interviews were done to identify the main issues associated with biofouling in marine and coastal heat exchangers.

25.3 Results

From the literature study and the interviews conducted, the major environmental and economic impacts due to biofouling in marine and coastal heat exchangers were identified. The environmental impacts are presented in Sect. 3.1 and the economic impacts in Sect. 3.2.

25.3.1 Environmental Impacts

This section describes the main environmental impacts due to biofouling in marine and coastal heat exchangers. The impacts are classified into three categories. A cumulative model of environmental impacts is presented in Fig. 25.1.

Category 1: Biofouling and the subsequent rise in global warming potential

A major issue associated with heat exchangers due to marine biofouling is the reduced heat transfer efficiency (Hansen 2018; Trueba et al. 2015). The fouling matter sticks on to the heat exchanger surface and reduces the efficiency of the heat exchanger to either transmit or absorb heat (Trueba et al. 2015). Considerable energy loss occurs due to reduced heat transfer at the heat exchanger surface (Kronholm 2018; Bertilsson 2018). The case study article ‘The Heat Transfer Resistance of Various

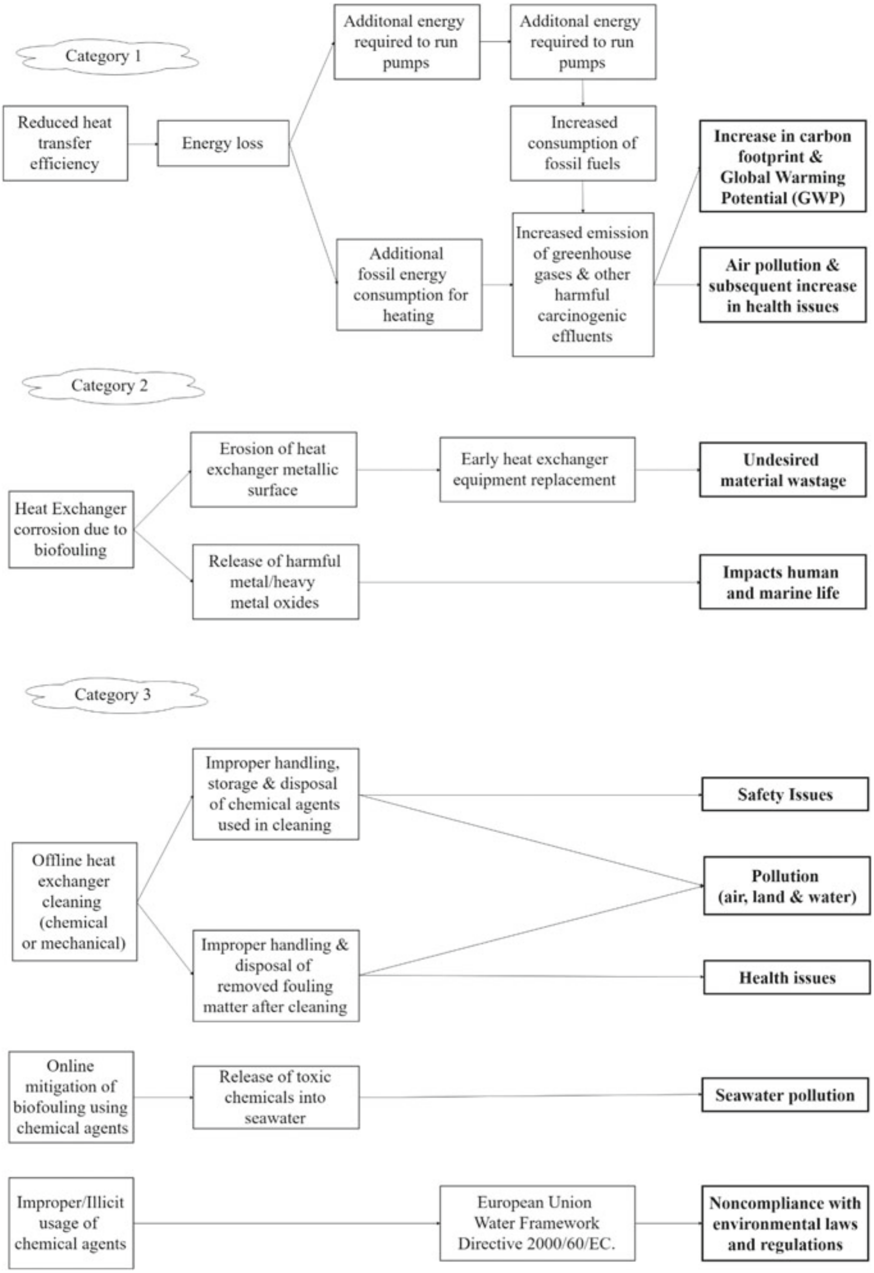

Fig. 25.1 Cumulative model of environmental impacts

Heat Exchanger Tubing Alloys in Natural and Synthetic Seawaters' published by Sheldon et al. in 1984 evaluates the impact of fouling on heat transfer efficiency of a condenser using tubing material Type 439 Stainless Steel (T439SS) (Sheldon and Polan 1984). The case study shows that one month of exposure to a biofouling environment reduced the heat transfer efficiency of the condenser by 19% (Sheldon and Polan 1984). Six months exposure of the same condenser in an inorganic depositing environment (calcareous or slit) only caused 9% reduction (Sheldon and Polan 1984). Thus biofouling could increase the heat transfer resistance to a greater degree in a much shorter time when compared to inorganic deposits (Sheldon and Polan 1984).

Therefore, to compensate for this energy loss at the heat exchanger surface, additional energy has to be supplied. In most cases, fossil fuels are the main energy source of heat exchangers that are used for heating purposes. Thus marine biofouling will directly result in additional consumption of fossil fuels (Casanueva-Robles and Bott 2005). More and more consumption of fossil fuels will increase the emission of air pollutants like CO_2, SO_2 & NO_X and thereby a subsequent rise in the global warming potential (GWP). The case study article 'The Environmental Effect of Heat Exchanger Fouling' published by Müller-Steinhagen et al. in 2005 proves that there is a direct relationship between the biofilm thickness on the heat exchanger surface and the overall CO_2 emissions in seawater cooled power plants (Casanueva-Robles and Bott 2005). A 550 MW coal-fired power station was considered for the case study (Casanueva-Robles and Bott 2005). In the power station, steam is condensed in seawater cooled high and low pressure condensers (Casanueva-Robles and Bott 2005). The steam is condensed in order to reduce the steam pressure, which will help to increase the pressure driving force across the turbines (Casanueva-Robles and Bott 2005). The biofouling affected the proper functioning of the condensers and increased the steam pressure, which resulted in the reduction of driving force across the turbines (Casanueva-Robles and Bott 2005). This resulted in subsequent energy loss and affected the plant's efficiency (Casanueva-Robles and Bott 2005). To compensate for this energy loss, more steam has to be produced and this caused more CO_2 emissions (Casanueva-Robles and Bott 2005). The CO_2 emissions were compared to different values of biofilm thickness on the condenser surface (Casanueva-Robles and Bott 2005). For both high and low pressure condensers, the biofilm thickness was considered from 0 to 10^3 μm (Casanueva-Robles and Bott 2005). The percentage increase in CO_2 discharge was 0.75% for low pressure condenser and 0.69% for high pressure condenser (Casanueva-Robles and Bott 2005). Thus for the thickest biofilm studied (10^3 μm), the total additional CO_2 produced was 6.2 tonnes per hour (Casanueva-Robles and Bott 2005). The case study concluded a significant proportional increase in power plant's overall CO_2 discharge with an increase in biofilm thickness on the condenser surfaces (Casanueva-Robles and Bott 2005).

Another example regarding CO_2 emissions caused by heat exchanger fouling is provided in the article 'Heat Exchanger Fouling: Environmental Impacts' published by Müller-Steinhagen et al. in 2011 (Müller-Steinhagen et al. 2009). In the article, the authors provide an approximate estimation of the overall annual CO_2 emissions caused by heat exchanger fouling in the oil refinery operations. To heat the crude oil, the oil refineries generally rely on a battery of shell & tube heat exchangers also called a crude preheat train (CPT) (Müller-Steinhagen et al. 2009). The decreased efficiency of these heat exchangers due to fouling is estimated to have a 10% increase in fuel usage (Müller-Steinhagen et al. 2009). The article states that, at a global scale, this corresponds to approximately 88 million tons per annum of CO_2 emissions in the oil refinery operations alone (Müller-Steinhagen et al. 2009).

In the case of marine heat exchangers that are used for cooling purposes, seawater is mainly used to absorb the excess heat generated. Biofouling causes the narrowing of the flow area and thereby result in reduced water flow or a pressure drop inside the heat exchanger (Kronholm 2018; Bertilsson 2018; Radicone 2009). This will also result in reduced heat transfer and energy loss. In order to compensate for the reduced heat transfer, more seawater has to be pumped. This will directly result in additional water consumption. Apart from that, the water pump consumes additional energy (electrical energy) to supply more seawater (Hansen 2018; Kronholm 2018). In most cases, electrical energy utilized for running the pumps is obtained through the burning of fossil fuels (Hansen 2018; Kronholm 2018). This will also increase CO_2 emissions and thereby an equivalent rise in the global warming potential.

Several other scientific studies and conferences like ‘Heat Exchanger Fouling and Cleaning X—2013’ & ‘Heat Exchanger Fouling and Cleaning XI—2015’ estimated that the heat exchanger fouling is responsible for 1 to 2.5% of overall global CO_2 emissions (Malayeri et al. 2015; Müller-Steinhagen et al. 2009, 2011). However, it is highly difficult to attain a cumulative value on the overall percentage of CO_2 emissions due to biofouling. This is because, the values will always vary according to factors like the severity of fouling, heat exchanger operating conditions, plant energy source and so forth (Müller-Steinhagen et al. 2009). Apart from that, the global energy consumption rate by the offshore industries is not declining but increasing every year. Therefore, the actual percentage of CO_2 emissions due to heat exchanger fouling could be much higher in reality.

Category 2: Heat Exchanger corrosion and environmental issues

Another major issue with marine biofouling is the corrosion that happens on the heat exchanger surface (Hansen 2018). The deposition of biofilms (either micro fouling or macro fouling) will lead to the development of special chemical environments that speeds up corrosion of heat exchanger metallic surface. If such biofouling is left unchecked, it will eventually result in material erosion on the heat exchanger surface and causes leaks, which requires effective maintenance and repairs. Frequent maintenance and repairs will reduce the equipment’s operational lifetime and lead to early scrapping/disposal of the product. Common heat exchanger materials are Titanium, Stainless Steel, Stainless Steel alloys, Copper alloys, Aluminium alloys, among others (Hjalmars 2014; Michels et al. 1979; Darby 1984; Kapranos and Priestner 1987). Thus biofouling corrosion leads to undesired material wastage. Moreover, in the case of corrosion, metal or heavy metal oxides could be also released to the atmosphere as by-products of fouling (Müller-Steinhagen et al. 2009). This could cause serious health issues that affect human and animal welfare (Müller-Steinhagen et al. 2009).

Category 3: Environmental issues associated with the process of biofouling mitigation or removal

Currently, there are many technologies employed in the industry for the prevention or the mitigation of biofouling in marine heat exchangers. The companies use online biofouling prevention techniques, offline biofouling prevention techniques or a combination of both (Müller-Steinhagen et al. 2011). The technique that will be adopted depends on several factors like the type of heat exchanger, type of fouling, severity of the fouling, cost and expenses related to the biofouling prevention technique, plant operational characteristics, the production capacity of the plant, seawater conditions, environmental regulations, climate conditions of the region where the heat exchanger is functioning and so forth. (Müller-Steinhagen et al. 2011). In the case of online techniques, the cleaning or removal of biofouling from heat exchanger surfaces is done without removing the heat exchanger from its current operation (Müller-Steinhagen et al. 2011). But in offline cleaning, heat exchangers have to be moved out of the current operation (Müller-Steinhagen et al. 2011).

A widely used online technique for the mitigation of marine biofouling in the industry is the application of chemical agents like biocides, antiscalants or antifouling agents (Kronholm 2018;Müller-Steinhagen et al. 2009). The dosage of these chemicals mainly depends on the type and the severity of fouling. These chemical agents can reduce the growth and deposition of biofoulants on heat exchanger surfaces. But, at the same time, they contain considerable amounts of chemicals like chlorine, polyphosphate, hypochlorite, coagulants bromine, zinc, among others (Kazi 2012). If the application process of chemical agents is not properly monitored, it could result in the release of chemicals to seawater. This leads to seawater pollution and affects marine life. It also leads to the violation of important environmental legislation such as Water Framework Directive 60/2000/EC of the European Union (Müller-Steinhagen et al. 2009, 2011).

A popular offline cleaning technique is the mechanical cleaning of heat exchangers using manual labour and chemicals. The removed fouling matter after the cleaning process could contain harmful bacteria, fungi, carcinogenic/radioactive matter & other microbial particles (Müller-Steinhagen et al. 2009). Improper disposal of these 'removed fouling matter' as well as the 'toxic chemicals used in the cleaning process' cause severe environmental pollution and health issues (Müller-Steinhagen et al. 2009). For example, the removed fouling matter could have the presence of Legionella (a pathogenic group of Gram-negative bacteria) (Bott 2006; Flemming 2002). Biofilms are known sources of Legionella pneumophila which causes a pneumonia-type illness called Legionellosis (Abdel-Nour et al. 2013). In addition to that, the inappropriate handling of chemicals while usage also results in safety issues (for example, burns) due to exposure to chemicals (Müller-Steinhagen et al. 2011).

The research study provides clear evidence that biofouling in marine and coastal heat exchangers lead to severe environmental, climate as well as health issues.

25.3.2 Economic Impacts

This section describes the major economic impacts due to biofouling in marine and coastal heat exchangers. The impacts are classified into four categories. A cumulative model of the economic impacts is presented in Fig. 25.2.

Category 4: Reduced heat exchanger efficiency and subsequent costs

From an economic perspective, the biggest problem caused by marine heat exchanger biofouling is the loss in production due to the reduction in heat transfer efficiency. For big industries like refineries and petrochemical plants, energy loss due to reduced heat transfer could result in a subsequent loss in their overall production. Additional energy has to be supplied to compensate for the energy loss. Fossil fuels are the commonly used energy source and with the increase in biofouling, the consumption of fossil fuels also increases. This will increase production costs (Hansen 2018).

To avoid these production losses and the costs associated with that, the heat exchanger users will try to increase the flow inside the heat exchanger. To increase the flow, higher capacity pumps have to be installed. This causes an increase in pump purchasing costs (Hansen 2018; Kronholm 2018). The increase in the pump cost is highly variable depending on the severity of biofouling in each case (Hansen 2018). Hence, it is difficult to provide an average range of values (Hansen 2018). The higher capacity pumps will result in high energy consumption (Kronholm 2018). As a result, the energy costs (mostly electrical energy) will also become higher with the increase in biofouling (Kronholm 2018). Thus resulting in a significant increase in the overall operational expenditure.

Category 5: Biofouling corrosion and subsequent costs

If the biofouling deposits formed on the heat exchanger surfaces are not timely removed, the fouling deposits will erode the surface. This affects the proper functioning of the heat exchanger and further decreases the heat exchanger life expectancy. Therefore, if left unchecked, biofouling will result in early heat exchanger replacement costs (Hansen 2018; Kronholm 2018; Bertilsson 2018). Further, biofouling corrosion will lead to leaks and call for unscheduled repair or maintenance. This will not only increase the maintenance expenditure for the end-user but also increase the operational expenditure due to unscheduled equipment downtime and subsequent loss of production (Hansen 2018). Frequent repair and maintenance of the heat exchanger will also reduce the equipment life and thereby leads to increased depreciation costs.

Category 6: Biofouling removal or mitigation costs

Therefore, to reduce the production loss and the additional operational & maintenance expenditure, the heat exchanger users will try to remove biofouling from the heat exchanger surface. There are both online and offline biofouling prevention techniques. Accordingly, there are various costs associated with these techniques.

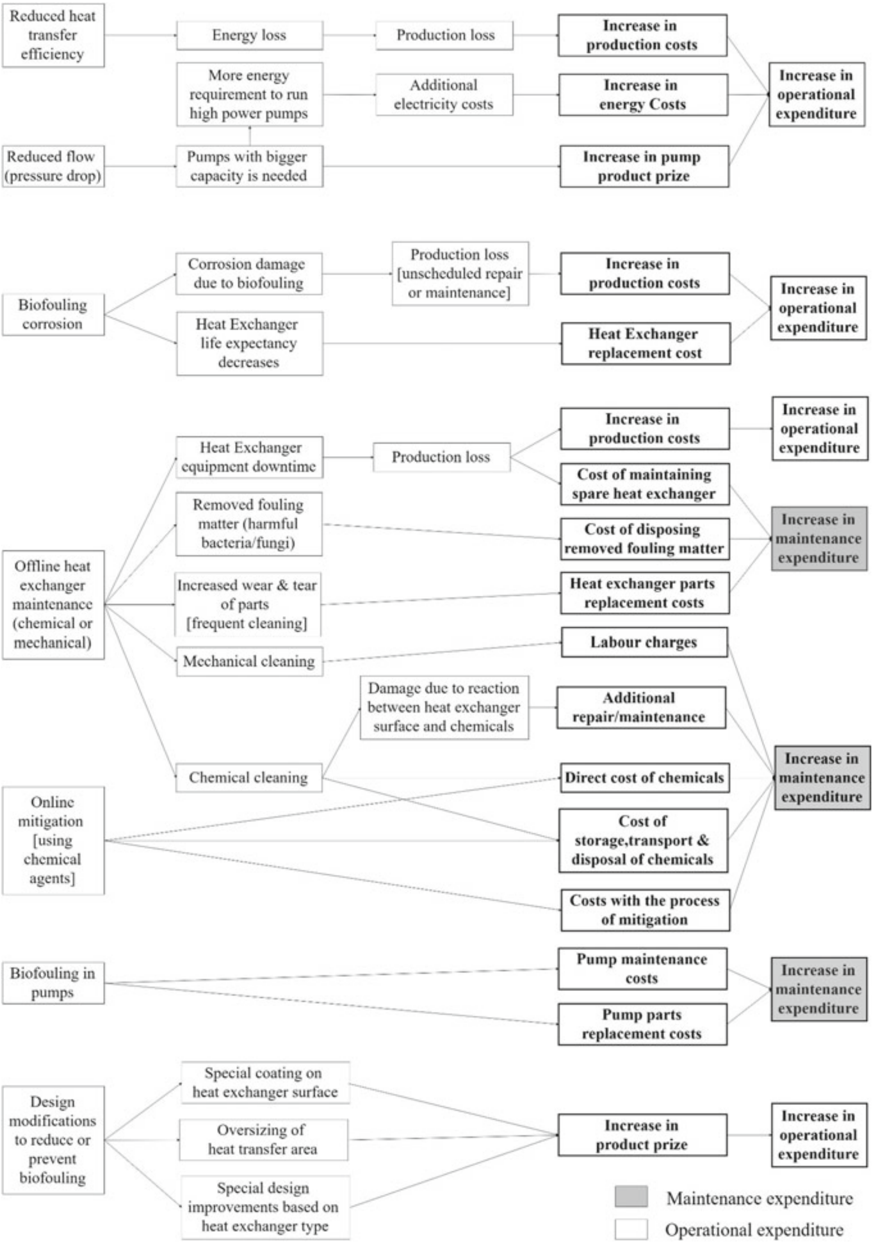

Fig. 25.2 Cumulative model of economic impacts

The main cost associated with online biofouling prevention is the direct cost of the chemicals that are used for the removal of deposits from time to time (Hansen 2018; Kronholm 2018; Bertilsson 2018). Then there are costs associated with the process of mitigation based on the mitigation techniques used. Due to strict environmental regulations, the storage, transportation and the proper disposal costs (treatment costs) of the chemicals used in the mitigation process become a significant factor in the overall costs associated with biofouling prevention (Hansen 2018). These costs are directly dependant on the rate of biofouling in each case. As the biofouling rate is a variable factor, it is difficult to provide an average range of values (Hansen 2018).

Biofouling causes the requirement of periodic offline cleaning of heat exchanger surfaces (Müller-Steinhagen et al. 2011). The cleaning schedules vary widely and depend mainly on the rate of biofouling which in turn depends on local characteristics like the plant operating conditions, physical and chemical properties of the process fluid, heat exchanger material properties, and so on (Michels et al. 1979). For example, some heat exchangers are cleaned daily, and some others weekly, monthly or even annually (Michels et al. 1979). In offline cleaning, the heat exchangers have to be removed from the operation and then disassembled (Hansen 2018). A popular cleaning technique is the mechanical cleaning of heat exchanger surfaces by employing manual labour (Hansen 2018; Chambon et al. 2017). The main cost associated with offline mechanical cleaning is labour charges (Hansen 2018; Kronholm 2018; Bertilsson 2018; Kazi 2012). Offline cleaning is also performed using chemicals (Kazi 2012). A major disadvantage with offline chemical cleaning is the potential for corrosion damage due to undesired reactions between heat exchanger surface and the chemical used (Kazi 2012). This would cause additional repair costs (maintenance expenditure) or even an early replacement of the heat exchanger if the corrosion effects are irreparable (Hansen 2018). There is also the direct cost of the chemicals used in the cleaning process. Further, as mentioned earlier in this section, the storage, transportation and proper disposal costs of the chemicals used in the cleaning process, also contribute to the total costs in the offline chemical cleaning process.

Offline biofouling cleaning techniques will cause significant equipment downtime as the heat exchangers are removed from the current operation. Thus there are also production losses associated with offline biofouling prevention. To prevent these production losses, usually, a spare heat exchanger will be maintained. So, there is also the additional cost of maintaining a spare heat exchanger. The pumps that are used to supply seawater to the heat exchangers are also subjected to marine biofouling. Thus biofouling will also result in additional pump maintenance costs or pump cleaning costs for the end-user (6). Apart from that, the frequent cleaning of heat exchangers and pumps to remove the deposits will cause wear and tear of heat exchanger parts and pump parts. This will decrease the life expectancy of parts and results in the increase of parts replacement costs and overall maintenance expenditure for the end-user.

Category 7: Heat exchanger design modifications due to biofouling

As biofouling is a major unresolved problem to the heat exchanger end-users, the heat exchanger manufacturing companies try to improve the heat exchanger resistance towards biofouling by improving their product design.

A generally referenced source for deciding fouling factors during the design of heat exchangers is TEMA (The Tubular Exchanger Manufacturers Association) (Diaz-Bejarano et al. 2017; Ross et al. 2015). One common method followed is to increase or oversize the heat exchanger heat transfer area to account for diminished performance due to biofouling (Diaz-Bejarano et al. 2017; Ross et al. 2015).

Design modifications are also done based on the type of heat exchanger. For example, for a shell and tube heat exchanger, a common solution is to increase the heat exchanger tube side velocities (Coletti et al. 2015). This increases the wall shear stress, and thereby less fouling material is deposited on tube surfaces (Coletti et al. 2015). In the same way, to prevent biofouling in a plate heat exchanger, one might undersize the unit to keep the turbulence high in the heat transfer channels.

Another common practice is to add effective surface coatings to mitigate biofouling related issues in marine heat exchangers (Santos et al. 2017). Silicone-based coatings and Polymer coatings based on the sol-gel process are widely used to resist fouling (Hjalmars 2014). More advanced fouling resistant coatings like Carbon nanotube-polytetrafluoroethylene, Nano-hybrid sol-gel coatings, Diamond-like carbon (DLC) coatings, among others, are formulated through research and development (Hjalmars 2014). All these design alterations will help to reduce biofouling, but will also increase the heat exchanger product cost in the market.

25.4 Discussion

The global energy requirement is increasing year by year. As heat exchangers are one of the most efficient means of heat transfer, the heat exchanger market is also growing, and the increase in the number of heat exchangers will cause a proportional increase in the environmental and economic impacts associated with heat exchanger biofouling. Thus, it is necessary to implement effective methods to reduce biofouling. Currently, there are various techniques adopted for biofouling prevention in marine heat exchangers. Primarily, the heat exchanger manufacturers would prefer to mitigate biofouling through the proper design of heat exchangers and then, the most adopted method is the use of online mitigation techniques (Müller-Steinhagen et al. 2011). Online methods are more preferred when compared to offline techniques as it will not affect the equipment availability.

Among different online mitigation techniques, the most common method is the use of chemical agents (Müller-Steinhagen et al. 2009). But, the presence of toxic substances in these chemical agents could greatly outweigh, from an environmental point of view, the benefits of fouling mitigation. Hence, it is significant to adopt more sustainable online biofouling mitigation techniques. Other online biofouling mitigation techniques include physical and mechanical methods. These methods do not involve the usage of chemical agents, but their applicability is limited and depends on various factors like the type and geometry of the heat exchanger, intensity of the fouling, operations conditions and so on (Müller-Steinhagen et al. 2011). Some examples of online mechanical methods consist of the usage of different cleaning projectiles (for example, sponge balls, and wire brushes) and tube inserts (for example, twisted tapes, coils, and wire matrix inserts) (Müller-Steinhagen et al. 2011). The examples of physical methods of online biofouling mitigation include the application of electric fields, sonic technologies, magnetic fields, ultraviolet light, and surface modifications using surface coatings (Trueba et al. 2015). Several quantitative efforts are currently ongoing to further develop and improve the online biofouling mitigation techniques so that they are more environment-friendly and at the same time economical. The successful implementation of such green initiatives in the market requires the combined and collaborative efforts of researchers, heat equipment manufacturing companies and also heat exchanger users [offshore industries].

25.5 Conclusion

The results from the literature review and the qualitative interviews conducted show that heat exchanger biofouling contributes to major environmental issues like global warming and climate change. From an economic perspective, marine biofouling increases both operational expenditure and maintenance expenditure in offshore industrial processes. Although the use of chemical agents is effective in fouling mitigation, it affects marine life and also causes significant health and safety issues to humans through air, land and water pollution. Hence, this paper highlights the need to develop and adopt new solutions for biofouling prevention in heat exchangers that are eco-friendly but at the same cost-effective. Further research, both qualitative & quantitative is needed to identify such sustainable biofouling prevention techniques, their effectiveness in preventing biofouling, and how these techniques could be introduced in the heat exchanger industry.

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