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Research Paper

Influence of the Reynolds number on the thermal effectiveness of tubular heat exchanger subjected to electromagnetic field-based antifouling treatment in an open once-through seawater cooling system

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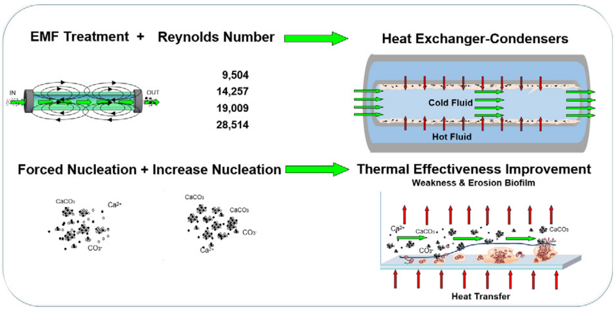
HIGHLIGHTS

- Biofouling adhesion under turbulence flow was investigated.
- Effectiveness-NTU during antifouling treatment is improved.
- Increasing the Re can improve the AF EMF treatment on a seawater cooling system.
- Re on biofilm characteristics is shown as important variable.

GRAPHICAL ABSTRACT



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ABSTRACT

Biofouling adhesion on heat exchanger surfaces reduces the thermal effectiveness of the heat transfer process. The main purpose of this work was to investigate the influence of the turbulent flow regime on an electromagnetic field (EMF)-based antifouling (AF) treatment in a tubular heat exchanger cooling seawater system and to determine the resulting effectiveness-number of transfer units (ε-NTU). Experiments were performed for turbulent flow corresponding to Reynolds numbers (*Re*) of 9504, 14,257, 19,009 and 28,514, which are normal operating conditions for tubular heat exchangers in which biofouling usually occurs. The best ε-NTU value was improved by 14% for the *Re* of 28,514 compared with the best value for untreated water. Furthermore, the *Re* assayed were associated with improved heat transfer resistance. The best AF rate was as high as 20% for a *Re* of 28,514. Additionally, the biofouling film for the case of seawater treated at 28,514 *Re* flow was thinner, with a lower concentration of solids, which improved the thermal effectiveness. The EMF-based AF treatment has great potential for improving thermal effectiveness and mitigating biofouling in tubular heat exchangers.

1. Introduction

The resulting energy losses in heat exchangers in which seawater is used as the coolant are a major concern in all sectors of industry. The presence of biofouling in heat exchangers represents a resistance to the transfer of heat and therefore reduces the effectiveness of the thermal process [1]. Biofouling on the inside surface of heat exchanger tubes drastically limits the heat exchangers' performances and causes a pronounced increase in heat transfer resistance [2]. Reduced thermal effectiveness of the heat exchangers due to biofouling represents an increase in energy consumption, with repercussions not only in cost but also in the conservation of world energy resources [3]. Biofouling

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Nomenclature

A	surface of tube wall, m^2
AF	antifouling
C	heat capacity, $W\,K^{-1}$
Cp	specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$
d	diameter, m
e	biofouling thickness, μm
EMF	electromagnetic field
L	tube length, m
$\dot{m}$	water mass flow rate, $kg\,s^{-1}$
l	test tube length, cm
q	heat transfer rate, W
r	test tube internal radius, cm
R	overall uncertainty in the result
R_f	heat transfer resistance without treatment, $m^2\,K\,W^{-1}$
R_f'	heat transfer resistance with EMF treatment $m^2\,K\,W^{-1}$
Re	Reynolds number
T	fluid temperature, K
U_D	overall heat transfer coefficient for the fouled condition, $kW\,m^{-2}\,K^{-1}$
Uc	overall heat transfer coefficient for the clean condition, $kW\,m^{-2}\,K^{-1}$
v	velocity flow, $m\,s^{-1}$
w	independent uncertainty in the measurement
W	total uncertainty in the measurement
X	independent variable

Greek symbols

ΔM	biofouling mass, g
ΔT_{LM}	logarithmic mean temperature difference
ΔR_f	increase from the initial value of the heat transfer resistance, $m^2\,K\,W^{-1}$
ρ_{bio}	biofouling density, $g\,cm^{-3}$
ε-NTU	effectiveness-NTU, (dimensionless)
λ_{bio}	biofouling is the biofouling thermal conductivity of the biofouling, $W\,m^{-1}\,K^{-1}$
μ	dynamic viscosity, $N\,s\,m^{-2}$
ρ	density, $kg\,m^{-3}$

Subscripts

ave	average
c	cold
h	hot
i	inlet
in	inner
min	minimum
o	outlet

deposits increase the overall thermal resistance, which can result in a substantial reduction in heat performance, increased corrosion of the heat exchanger wall, or the formation of obstacles to fluid flow, leading to an increase in operating costs. The accumulation of biofouling on the heat exchanger wall further affects the average temperature and the heat transfer coefficient. Hence, determining how to prevent biofouling on the heat exchanger wall is a critical problem [2–5].

Biofouling consists primarily of polysaccharides and water. In fact, the water content of biofouling material is typically greater than 80% [6]. The components of polysaccharides vary depending on species but typically include repeating oligosaccharides such as glucose, mannose, galactose, and xylose, among others. The precipitation of divalent cations (such as calcium and magnesium) in biofouling leads to an interaction between carboxylate functional groups on the polysaccharides and the divalent cations, resulting in a bridging effect between polymer chains. Bridging and crosslinking of the polymers stabilise the biofouling, making it more resistant to shear and more difficult to remove [7,8]. Hence, the biofouling that develops will interfere with the thermal effectiveness.

Seawater-cooled heat exchangers face more challenges than freshwater systems, particularly the increased biofouling arising from the higher microbiological activity in seawater as well a reduction in the heat transfer rate as a function of increasing dissolved cations (Na^+, Mg^{2+}, Ca^{2+} or K^+) and anions (Cl^-, SO_4^{2-}, CO_3^- or HCO_3^-) [6]. These ions result in excessive mineral precipitation (especially calcium and magnesium ions) because the conduction and convention of seawater is the primary mode of heat transfer in seawater-cooled heat exchangers, leaving the mineral ions behind. In particular, the reaction of calcium ions with carbonate ions in water causes layers of calcium carbonate ($CaCO_3$) to deposit onto heat transfer surfaces, decreasing the thermal effectiveness of heat exchangers because of the insulating effect of the deposits. Furthermore, the formed deposits reduce the flow area, thus requiring more pumping power to achieve the flow rate of water corresponding to the clean state [9].

EMF-based treatments are used for scale control in industrial processes using tap water and natural water [10–13]. The effect of EMFs on water properties depends on the nature and condition of the water, such as its alkalinity, pH, conductivity, and hardness [14–16]. The required duration of exposure of water flow to EMFs for effective treatment is on the order of 10^{-1} s; however, in cases of stationary water subject to a static magnetic field, the duration of exposure should be higher [17]. EMFs are physical tensor fields produced by electrically charged elements that affect electrically charged particles, thus having the capacity to precipitate mineral ions dissolved in water as $CaCO_3$, silicates and sulphates. $CaCO_3$ is polymorphous and can take the microcrystalline forms of calcite, vaterite or aragonite [12]. Aragonite and vaterite are kinetically favourable and may appear as a first form, recrystalising to calcite during ageing of the precipitate. Vaterite is the least stable anhydrous polymorph, whereas aragonite is stable when precipitated from carbonically pure waters at a temperature above 60 °C [18]. Therefore, if the kinetically favourable crystal type of $CaCO_3$ can be formed before the water enters the heat exchanger, biofouling deposition may be reduced or prevented [2,19]. This precipitation without adhesion to the surface affects the intermolecular interactions among extracellular polymers, thereby weakening the biofouling matrix and reducing its adhesion capacity, hence preventing the formation/adherence of the precipitates onto the walls of the heat transfer surfaces [20].

The Reynolds number (*Re*, dimensionless) defines the flow characteristics in a hydraulic system of determined length for a given speed, indicating the loss of energy caused by viscous effects. The flow becomes laminar at $Re \le 2100$, where viscous forces are the dominant effect on energy losses. Flow becomes turbulent at $Re \ge 4000$ because the viscous flow forces have little influence on the loss of energy. In the turbulent regime, the flow particles move chaotically and do not follow defined trajectories. At higher fluid velocity, a higher *Re* indicates a greater level of turbulent flow inside tubes [21]. The *Re* has an appreciable influence on the biofouling rate. The *Re* affects the deposition rate and the removal rate through hydrodynamic influences such as turbulent eddies and shear stresses at the heat exchange surface [22]. The biofouling growth is dependent on the dissolved precipitates and operating conditions, such as the flow velocity and temperature. An increase in fluid velocity increases the turbulent regime and interaction of the dissolved ions that crystallised into particles, which become suspended in the flow. Therefore, EMF treatment could be improved by increasing the flow velocity [13].