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Thermohydraulic and thermoeconomic performance of a marine heat exchanger on a naval surface ship

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HIGHLIGHTS

- We conduct an investigation on fouling of a heat exchanger for naval applications.
- A model to predict heat exchanger fouling is presented.
- Results from the model are consistent with experimental data.
- Elements of fouling cost are presented.
- An optimum cleaning cycle based on cost is presented.

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ABSTRACT

Fouling of heat exchangers is a major problem on naval surface ships and submarines as well as commercial vessels and land-based cooling systems. Fouling of heat exchangers causes the thermohydraulic performance of heat transfer equipment to decrease with time. The heat exchanger must be cleaned as the thermal hydraulic performance decreases to a minimum acceptable level. The decision regarding periodic cleaning of a heat exchanger is generally based on the thermoeconomic performance of the process. In this article, freshwater (as coolant) and seawater temperatures and pressures through a seawater cooled shell and tube heat exchanger during 2500 operating hours have been measured, and total fouling resistances have been calculated. There is a good agreement between the model and the experimental fouling resistances. The dimensionless cost model and its variation with the dimensionless time are examined by considering the various cost elements for the heat exchanger. An optimum cleaning cycle for the case heat exchanger has been offered to minimize the total operating cost.

1. Introduction

The engines of a ship need cooling, similar to other ordinary engines. However, a ship uses seawater to cool its engines. The cooling process in a main diesel engine is a closed type of cooling system; in these types of systems, the engine is first cooled by fresh water, and the fresh water is then cooled by seawater. This closed type of cooling system is commonly used in all modern medium and high-speed diesel engines. The performance of heat exchangers in this process affects the cost of the final product, and unfortunately, these heat exchangers are subject to fouling as a result of the nature of the fluids flowing inside them. This causes a reduction in heat transfer that has a negative impact on product cost.

Therefore, to reduce this negative impact, heat exchanger performance should be monitored, and the heat exchanger should be cleaned at intervals that are determined according to optimal economic criteria. But despite the enormous cost associated with fouling, very limited research has been done on this subject. A user guide about fouling was published during the use of seawater as coolant by S.J. Pugh et al. [1]. It was stated that heat exchanger fouling in general is a major economic problem, accounting for 0.25% of the gross domestic product (GDP) in the highly industrialized countries [1]. E. Nebot et al. [2] proposed a kinetic model for fouling evolution prediction for power plant steam condensers cooled with seawater. The fouling effects of seawater on a 90/10 Cu/Ni commercial heat exchanger tube were investigated by M. Izadi et al. [3]. However, a fouling model and cost were not considered. A novel method for on-line determination of the thermal resistance

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of fouling in shell and tube heat exchangers was presented by M. Markowski et al. [4]. There has been no investigation into a cost-based cleaning cycle model of a marine heat exchanger subject to fouling for a naval ship application. In this study, we discuss the performance and optimum cost-based time for cleaning the exchanger onboard on a case naval ship.

2. Heat exchanger fouling and its effects

A heat exchanger is a device that provides a flow of thermal energy between two or more fluids at different temperatures. Fouling can be defined as the accumulation of undesirable substances on a surface. The lower heat transfer and increased pressure drop resulting from fouling decreases the effectiveness of a heat exchanger [5]. According to S. Kakaç and H. Liu [5], fouling can be classified into the following categories: particulate fouling, crystallization fouling, corrosion fouling, biofouling, and chemical reaction fouling. Of the above mechanisms, the ones presenting most of the problems for seawater systems are corrosion fouling and biological fouling [1]. The fouling mechanisms, based on Epstein's classification, are initiation, transport, attachment, removal, and aging [5]. Fouling mechanisms have been studied to a great extent [6–10].

3. Monitoring heat exchanger performance

The heat transfer rate, Q, in a heat exchanger is expressed as:

$$Q = UA_o\Delta T_m \tag{1}$$

where U is the overall heat transfer coefficient, A_o is the outside heat transfer surface area of the tube, and ΔT_m is the log mean temperature difference [5], which can be written as:

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\frac{\Delta T_1}{\Delta T_2}} \tag{2}$$

The overall heat transfer coefficient for a fouled surface can be written as:

$$\frac{1}{U_f} = \frac{1}{U_c} + R_{ft} \tag{3}$$

where U_f and U_c are the overall heat transfer coefficients for the fouled and the clean surfaces, respectively. R_{ft} is the total fouling resistance and is given as [5]:

$$R_{ft} = \frac{A_0}{A_i}R_{fi} + R_{fo} \tag{4}$$

where the subscript f refers to the fouled conditions.

Process conditions usually set the heat duty and fluid temperatures at specified values [4]:

$$Q_f = Q_c \tag{5}$$

$$\Delta T_{mf} = \Delta T_{mc} \tag{6}$$

where ΔT_1 is the temperature difference between the fluids at one end of the heat exchanger, and ΔT_2 is at the other end.

The fouling resistance can be related to the fouling thermal conductivity k_f and the fouling thickness t_f for a cylindrical tube wall [4] as:

$$R_f = \frac{d_c \ln\left(d_c/d_f\right)}{2\pi k_f} \tag{7}$$

4. Modeling of fouling in heat exchanger

The formation of only one type of fouling on heat transfer surfaces is impossible. Most deposits that occur on heat transfer surfaces are the result of two or more of the fouling types described. However, in most cases, one type of fouling will be dominant. It has been assumed a single foulant and a single mechanism for the modeling of the fouling of heat exchangers in Refs. [7–10].

Variation of fouling with time is expressed as the difference between a deposit rate and a removal rate [5,7,11]:

$$\frac{dR_f(t)}{dt} = \varphi_d - \varphi_r \tag{8}$$

where dR_f/dt is the rate of change of fouling resistance with respect to time.

A more suitable measure of the actual fouling process is the deposition mass per unit area. The fouling resistance of the deposit can be converted to mass (per unit area) by using the following expression [8]:

$$m_f = R_f\rho_f k_f \tag{9}$$

where ρ_f (kg m^{-3}) and k_f (W/mK) are the density and the thermal conductivity of the deposit, respectively.

So the general equation representing the fouling rate can be stated as [7,8]:

$$\frac{dm_f(t)}{dt} = \varphi_d - \varphi_r \tag{10}$$

and the removal rate, mass of fouling detached per unit time and per unit surface area, is [8]:

$$\varphi_r = bm_f \tag{11}$$

which, upon integration, assuming φ_d is constant, becomes [8]:

$$m_f(t) = m_f^*[1 - \exp(-bt)] \tag{12}$$

where m_f^* is the "steady state" maximum amount of deposit, and b is a parameter that represents the inverse of the resistance of the deposit to removal [8]:

$$m_f^* = \varphi_d/b \tag{13}$$

4.1. Driving assumptions

The following considerations have been adopted:

1. (1) Fouling occurs on both sides of the heat transfer surface.
2. (2) Fouling inside the tube is assumed to be biofouling.
3. (3) Fouling outside the tube is assumed to be particulate fouling.
4. (4) Fouling inside and outside of the tube is circular.
5. (5) Volumetric flow rates of the freshwater and seawater pumps are constant.
6. (6) Fluid properties are constant.

4.2. Modeling of fouling resistance inside the tube

Fouling inside the tube can be assumed to be biofouling, because seawater flows through the inner tube. Marine heat exchangers using seawater are prone to biofouling. Pugh et al. [1] reported that the rate of biological fouling increases with temperature up to