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Incorporating the Use of a Fouling Model in the Design and Operation of Cooling Networks

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The importance of knowing how fouling develops and deteriorates the thermal-hydraulic performance of heat transfer processes becomes evident when the problem is already there and is difficult to eliminate. Fouling prediction is important in grassroot design and even more, in retrofit applications. The aim of the present work is to show the use of a fouling model to predict scaling in cooling systems in order to derive design guidelines. Fluid temperature and velocity are the two more important variables that determine the rate at which scaling takes places. This work focuses on retrofit of existing cooling systems for situations where new heat exchangers need to be incorporated into the network. It is shown how the pressure drop, fluid velocity and flow distribution are affected depending on the decision of where to place the new exchangers. All these factors are intimately related to the development of fouling. The model presented in this work includes the prediction with time of the increase of pressure drop and flow redistribution as fouling builds up. The use of the model is illustrated through a case study that shows that in the retrofit of cooling systems, the incorporation of new heat exchangers in parallel is recommended.

1. Introduction

Heat exchangers used in cooling networks are subject to fouling due to scaling as a result of various situations: poor cooling water treatment, exchanger overdesign with low fluid velocities and excessive water temperature rise across the cooler. The use of accurate fouling predicting models is fundamental for simulations to be meaningful. Most of the common flaws in predicting models are the over prediction of fouling rates or lack of sensitivity to incorporate the effect of fluid velocity in the reduction of the fouling rates (Lugo-Granados and Picón-Núñez, 2017). When applied in design, the information that fouling can provide can be used in various ways: to determine the effect of fouling over time to plan cleaning strategies, or to understand the interaction between the various components of a cooling network such as the cooling tower, coolers, pumps and the piping. Souza and Costa, 2019, developed a comprehensive simulation model for cooling networks that integrates the main components and includes the effect of scaling as the most important type of fouling in the cooling fluid.

Knowledge of the water temperature distribution along a cooling circuit network is important for decision making during operation. One of the approaches to carry out this type of simulations is based on the training of neuronal networks (Malinowski et al., 2011). In operation, control of the water return temperature is vital for the reduction of fouling. In design, water return temperatures can be kept at low values through the relative position of coolers. When coolers are positioned in parallel, the return temperature tends to be low while the placing of coolers in series increases it. However, since fluid velocity has an important effect upon fouling with larger velocities reducing the rate of deposition, the series arrangement tends to be more favorable than the parallel arrangement as they exhibit higher velocities. There is therefore a minimum necessary operating velocity for a given return temperature as demonstrated by Ma et al. (2018a).

Cooling systems design has been approached by fixing the maximum return temperature and optimizing the operation cost. In their work, Zheng et al. (2018), dealt with the problem of multiple tower design by means of mixed integer nonlinear programming. The approach does not consider the design of coolers and the effects of fouling. In a different approach, Liu et al. (2018) present a design methodology based on the optimization by MINL where the design of coolers is included and water flow rates are optimized as well. Additionally, the

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optimization of multi-plant cooling systems can be approached form the point of view of the need to reduce the pumping power as presented by Ma et al. (2018b). Since fouling is an unavoidable operating problem, failure to consider it right at the design stage will cause operating problems in the long time.

An important issue related to the consideration of fouling at the design stage is the choice of the most appropriate fouling factor to use. Use of the excessive values will inevitably lead to overdesign which in turn results in lower fluid velocities that enhances fouling. The problem becomes even more intricate when dealing with the incorporation of new exchangers into existing cooling networks. Picon-Núñez et al. (2012) analyzed the effect of introducing new exchangers into existing networks and produced a methodology to study the thermohydraulic performance of the network by considering the incorporation of new units in a new parallel line, in series with existing units and in parallel with an existing exchanger to increase the heat load. What is appreciated from this work is that the placing of new units modifies the water distribution along the network, however, this analysis still lacks the incorporation of fouling and its effects upon the thermohydraulic performance of the system.

As the flow rate across the network is modified, this influences the growth of fouling. If fouling is increased, the pressure drop will also increase causing a further re-distribution in flow rate. Therefore, the aim of the present work is to bridge this gap and to extend the thermohydraulic analysis of cooling networks for the cases of retrofit by considering the simultaneous effects of fouling rates, flow distribution and thermal performance. A validated fouling model is used to predict the thermohydraulic performance of coolers and the growth of fouling with time.

2. Methodology

This section describes the models used to determine the fouling rates in coolers, flow water distribution in piping networks and the pump operating analysis to determine the interactions of fouling and flow rate in cooling network retrofit situations. Water temperature, concentration, velocity, and pH are the operating conditions that most affect the net rate of fouling due to scaling in a cooling system. The net rate of fouling considers both the rate of deposition to the surface and the rate of removal from the surface. The sensitivity of a model to account for the effects of velocity depends on whether the inertial and viscous effects are accounted for. A model based on the laminar layer theory assumes that it is within this region that the chemical reaction for the formation of the $CaCO_3$ takes place. For the case of tubular exchangers, Lugo and Picón (2018) considered the use of a parameter to account for the inertial and frictional effects obtained from experimental data published from various research groups. The result is Eq.(1).

$$\dot{m}_d = \frac{\beta}{2}\left(\frac{\beta}{\alpha\, k_r} + (C_1 + C_2) - \sqrt{\frac{[\beta + (C_1 + C_2)\,\alpha\, k_r]^2 + 4\,\alpha^2\, {k_r}^2 (K_{sp} - [C_1][C_2])}{\alpha^2\, {k_r}^2}}\right) \tag{1}$$

Where m_d is the mass flux (kg/m^2s); C_1 and C_2 are the concentration of Ca^{2+} and CO_3^{2-} (kg/m^3) contained in the water; K_{sp} (kg^2/m^6) the solubility of calcium carbonate; k_r ($m^2/kg\ s$) is the rate of reaction which is a function of temperature and is obtained from the Arrhenius equation, where the activation constant and frequency factor in the equation at a temperature range typical of the operation of cooling systems are: E=113 kJ/mol and k_0=2.05x1015 $m^4/kg\ s$ (Agustin and Bohnet,1995). β (m/s) is the mass transfer coefficient obtained from the following expression for turbulent flow (Re>4000) in tubes:

$$\frac{\mathrm{d}\,\beta}{D_{AB}} = 0.023\,\bar{u} Re^{0.83} Sc^{1/3} \tag{2}$$

Where d is the tube diameter (m); D_{AB} is the diffusivity of the chemical species ($0.79x10^{-9}$ m^2/s), $\bar{u}$ is the fluid average bulk velocity (m/s) and Sc is the Schmidt number (μ/ρ D_{AB}). The parameter α, is the dimensionless correction factor that incorporates the inertial and viscous forces and is expressed by Eq.(3).

$$\alpha = a(\mathrm{f} \times \mathrm{Re})^b \tag{3}$$

Where a= 0.12 and b=-1. The pressure drop in a pipe can be related to the volumetric flow rate in the following way:

$$\Delta P = KV^2 \tag{4}$$

Where *K* is the flow resistance, *V* is the volumetric flow rate and ΔP is the pressure drop. In cases of a series arrangement (Figure 1(a)), the total flow is the same for all the exchangers with the total pressure drop being the summation of the contribution of each exchanger. The expression for the total pressure drop is:

$$\Delta P = \sum_i K_i (V^2) \tag{5}$$

In a parallel arrangement, the pressure drop of each line is the same independently of the number of exchangers. However, the flow rate is different in each line. This reasoning applies to a combination of series-parallel arrangements as the one shown in Figure 1(b).

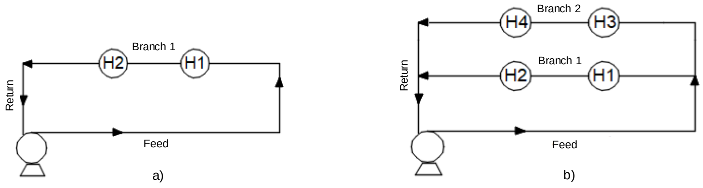


Figure 1: Cooling network: a) series arrangement, b) Series-parallel arrangement.

For a network composed of two lines or branches, the total volumetric flow rate can be expressed as:

$$V = V_1 + V_2 = \sqrt{\Delta P / K_{B1}} + \sqrt{\Delta P / K_{B2}} \tag{6}$$

Combining Eq.(4) and (6), the total resistance of a two-branch network is represented by Eq.(7):

$$K_{1+2} = \Delta P / V^2 = 1/[(1/K_{B1})^{0.5} + (1/K_{B2})^{0.5}]^2 \tag{7}$$

Therefore, the total flow rate for a two-branch system can be obtained from:

$$V_{1+2} = \sqrt{\Delta P / K_{1+2}} \tag{8}$$

If the volumetric flow rate through a single branch is:

$$V_1 = \sqrt{\Delta P / K_{B1}} \tag{9}$$

Then, the flow rate fraction through each branch is:

$$V_1 / V_{1+2} = \sqrt{K_{1+2} / K_{B1}} \tag{10}$$

The pumping system of a cooling network must always be evaluated when new exchangers need to be incorporated into the existing system. Failure to do this may result either in a reduction of the total water total rate or the need to replace pumps. The hydraulic behavior of reciprocating pumps is specified by its characteristic curve. These represent the relationship between volumetric flow rate with other parameters such as discharge pressure, efficiency that also depend upon the size, design and construction features of the pump. A typical characteristic curve is shown in Figure 2. This diagram shows the relationship between the total capacity of the pump and the capacity demanded by the process. The point where these two curves intercept indicates the operating conditions of the pump. At point A of Figure 2, the pump operates at higher power consumption than point B for the pressure drop of the system is higher; however, at point B, the pump operates at higher volumetric flow rate. The curves of the system are related to the pressure drop, with the pressure drop being the combination of all the contribution due to height, friction and flow through fittings and accessories of the system.

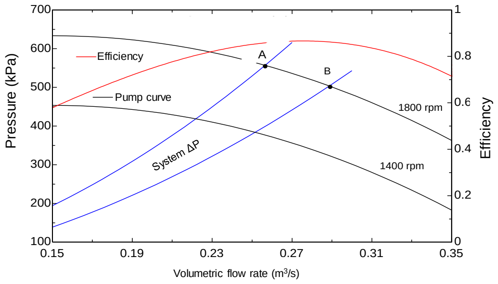


Figure 2: Typical characteristic curves of a centrifugal pump.

3. Case study

To analyze the effect of fouling on flow distribution on an existing cooling network, the system shown in Figure 3 is considered. The flow distribution through each branch is analyzed in three different scenarios: 1) a condition free from fouling; 2) a condition with fouling using a fixed value for the fouling factor, and 3) considering fouling and modeling its growth with time. The geometry of the system and the design features of the exchangers are given in Tables 1 and 2.

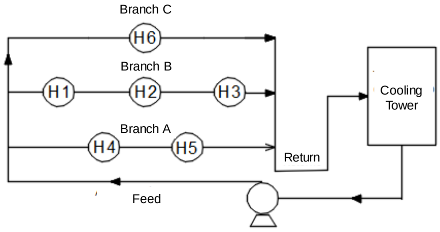


Figure 3: Cooling network for case study.

Table 1: Pipe dimensions.

Component	Diameter (m)	Length (m)	Elevation(m)
Feed	0.35	200	0
Brach A	0.25	120	5
Branch B	0.2	170	5
Branch C	0.2	180	10
Return pipe	0.35	200	0

Table 2: Geometrical features of heat exchangers.

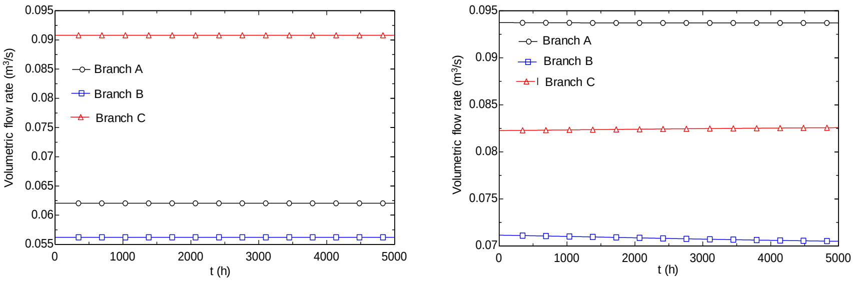
	H1-B	H2-B	H3-B	H4-A	H5-A	H6-C
K valve [Pa s/m^3]	9	9	9	9	9	9
No. Tubes	820	450	800	400	850	800
No. Passes	2	2	2	2	2	2
Cold fluid [kg/s]	85	85	85	85	85	85
Hot fluid [kg/s]	70	70	70	70	70	70
T_{Ci} [°C]	20	TCO1	TCO2	20	TCO4	20
T_{Hi} [°C]	110	90	85	85	100	120
L [m]	6.1	6.1	6.1	6.1	6.1	6.1
Di [m]	0.0148	0.0148	0.0148	0.0148	0.0148	0.0148
R [m^2 °C/W]	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005

4. Results

Figure 4(a) shows the way flow distributes in the system when there is no fouling. Figures 4(b) shows the case of a fully established fouling considering a fix value. Under no fouling conditions, a larger amount of water flows through branch C (Figure 4(a)) that has only one exchanger despite being at a higher altitude. When fouling is considered using a fixed value (0.0005 m^{2}°C/W), the flow rate through branch A is now larger since the flow resistance has now changed being lower for this branch. When a variable fouling resistance is analyzed, the flow rate changes with time as shown in Figure 5(a). For branches A and B the flow rate decreases but increases in branch C. The reason for this is that the water temperature is higher in these branches as they have more exchangers and fouling builds up faster. The flow resistance with time can be observed in Figure 5(b). For branches A and B the flow resistance grows with time but for branch C remains almost constant.

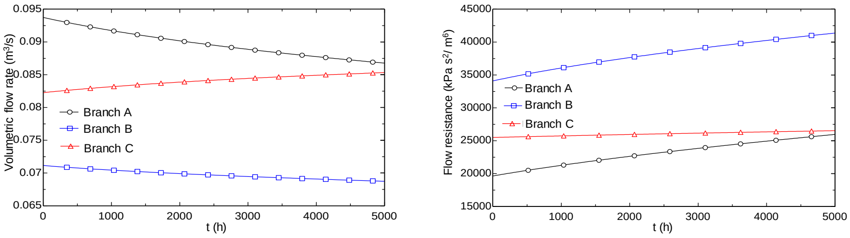
4.1 Retrofit of the cooling system

The need for increased heat removal leads to the incorporation of additional surface area into existing cooling networks. A new heat exchanger can be positioned in different ways: in a totally new branch in parallel or in series in an existing branch. The option of placing it in parallel with an existing heat exchanger to increase its heat load is not considered in this case study. Figure 6(a) shows the installation of the new exchanger in series and Figure 6(b) the insertion as a new branch. The incorporation of new exchangers causes the system to change the total flow distribution for two reasons: the increase of pressure drop due to the new unit and the increase of fouling. When a new branch is added in parallel, the pressure drop of the system reduces. This causes an increment in the flow rate delivered by the pump (Figure 7(a)). However, as time passes, the build-up of fouling increases the pressure drop (Figure 7(b)) and causes a reduction in the flow rate. If the new exchanger is added in series in branch C, the total flow rate reduces since the total pressure drop of the system is now higher (Figure 7(a)). This also causes the pressure drop and the flow resistance to increase with time (Figures 7(b) and 8(a)).



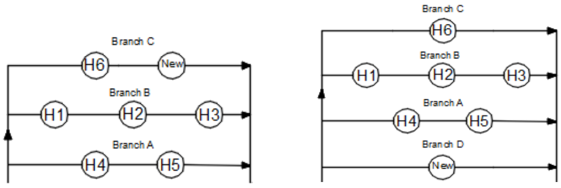
a) b)

Figure 4: Volumetric flow rate distribution: a) with no fouling, b) with fix fouling resistance.



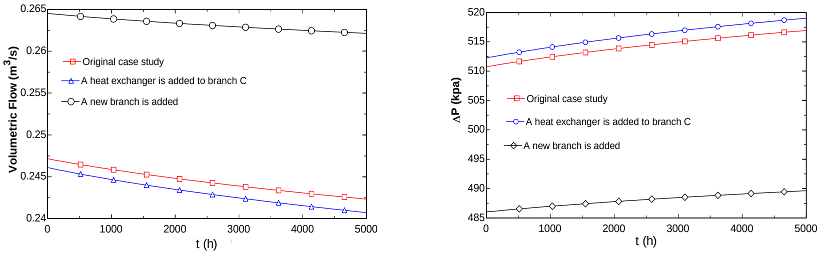
a) b)

Figure 5: Effect of variable fouling resistance on: a) flow distribution, b) Fouling resistance with time.



a) b)

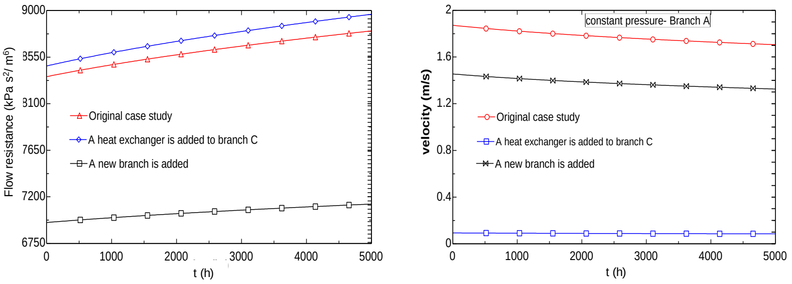
Figure 6: Retrofit of a cooling network. Incorporation of a new exchanger: a) in series with an existing branch, b) in a new parallel branch.



a) b)

Figure 7: Network changes with time: a) change in flow rate, b) pressure drop change.

Figure 8(b) shows the variation of velocity in branch A. Adding a new exchanger either in a new branch or in series in an existing branch causes the velocity in branch A to move to lower values. The rationale behind this is that, when a new branch is added in parallel, the total pressure drop reduces, even though the pump can now increase its flow rate, the flow must distribute among more branches. The increase of flow rate will not make up for the need to send certain flow rate through the new branch. The consequence is that the velocity in branch A is reduced. In the case of the new exchanger being positioned in series, the pressure drop reduction causes the pump to reduce its flow rate. Therefore, the velocity in branch A and on all other branches reduces. Lower velocities in the system will inevitably result in increased fouling rates.



a) b)

Figure 8: Variation of network performance with time: a) Flow rate resistance, b) velocity on branch A.

5. Conclusions

This paper introduces a methodology to determine the detrimental effects with time of fouling on cooling systems. The build-up of fouling creates flow rate disturbances that come about as a result of increased pressure drop. Flow rate redistribution along with the increased fouling resistance create detrimental thermal affects. If new coolers are placed in an existing cooling network, the flow rate will also redistribute creating further thermal disturbances. Unless the effect of these changes is considered, the heat removal rate of the system is likely to fall short from specifications. The approach presented in this paper aims at providing the required tools for cooling systems assessment. The main conclusions of this work are:

- The flow rate distribution of water in a cooling network is very sensitive to any change in the pressure drop conditions; such changes affect the heat transfer removal capacity of coolers and the outlet temperatures of the process streams.
- In operation, the build-up of fouling is the main source of pressure drop changes.
- Installation of new units in an existing cooling network causes redistribution of flow rate and changes in fouling deposition.
- To maintain fouling at low rates, cooling systems must be designed such that the return temperature does not exceed a maximum value and the flow velocity in coolers is above a minimum value.
- The impact of fouling on the thermohydraulic performance of a cooling system depends on the combined effect of fluid velocity, water maximum outlet temperature and foulant concentration.

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