THE DYNAMIC BEHAVIOUR OF ONCE-THROUGH COOLING WATER SYSTEMS UNDER FOULING PHENOMENA

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ABSTRACT

Fouling in thermoelectric power plant cooling systems may increase the backpressure of the steam turbine and cause deleterious effect in the thermal performance of the power plant. A complete analysis of the condenser must handle the exchanger as an integrated part of an entire cooling system, that is highly affected by the temperature and the cooling water quality parameters. The proposed model adopts a graph based network approach and includes the pump water supply, the associated pipes, and the steam condenser itself. It is able to describe the behavior of the system during a determined operation horizon where the effects of the temperature and water quality are associated to a fouling rate model due to the precipitation of calcium carbonate. The main results describe the performance decay of a hypothetical once-through steam condenser system including a horizontal condenser - due to fouling.

INTRODUCTION

The performance of a thermoelectric power plant is directly related to its cooling water system. The main task is to condense the exhaust steam from the corresponding thermodynamic cycle. Nevertheless, under certain scenarios, the formation of fouling can increase the thermal resistance and the backpressure of the steam turbine. This is particularly relevant in once-through cooling systems, where water is pumped from an outside source, flows through the heat exchangers and then is discarded to the environment.

Revealing the relevance of such systems, the literature contains several papers that investigated the modelling and simulation of steam condensers such as the model for steam condensers including the effect of in-leakage air [1]. Despite the good accuracy of the available models, the literature does not consider impact related to the quality parameters (e.g. suspended solids, pH, conductivity, hardness, etc) and conditions of the water in the condenser during an entire operation horizon, particularly involving fouling problems.

Due to the complexity of this system, an appropriate analysis of the condenser must handle it as an integrated part of an entire cooling system, which is highly affected by the cooling water behavior. For that, it must include the modelling of all network elements simultaneously and also the fouling effects [2].

The proposed model is able to describe the behavior of a once-through steam condenser system during a fixed operation horizon using a graph-based network approach to include in the analysis the
water supply pump, the associated pipes, and the steam condenser itself.

The effects of the temperature and water quality are associated to an inorganic fouling rate model, can describe the impact of the fouling layer on reduction the overall heat transfer coefficient, but also on increasing the flow resistance associated to the reduction of the free flow area.

**INVESTIGATED SYSTEM**

This paper focuses on once-through cooling water system that feeds the tube side of a large scale film condenser that receives the low pressure steam of a steam turbine as illustrated in Figure 1.

In order to guarantee sufficient heat exchange area to condense large amounts of low pressure steam, the steam power plants condensers are designed with large dimensions and high number of tubes. The cooling water flows inside the tubes surrounded by condensate in the shell, where it is collected through the lower compartment of the condenser (hot well).

The vertical position of each tube row in the bundle is identified according to variable \( z \) (from top to bottom, first row corresponds to \( z = 1 \)), that is relevant for the calculation of the external convection coefficient on each tube (Equation 2).

**NETWORK MODEL**

The process modeled in this paper has different pieces of equipment that are interconnected and intimately related. The heat exchanger itself is modeled as a set of tubes that have mass, momentum and heat balances calculated for time \( t \) and normalized axial position \( x \) coordinates varying from 0 to 1. In this context, the best approach to organize the model is to define a network structure using a digraph \([3]\) composed of \( |E| \) edges and \( |V| \) vertice, where:

- Vertices are identified by \( v_i \in V \), where \( i \) is the corresponding index, representing the network elements as: pumping supply vertex (subset \( SV \), representing the natural water source), fixed pressure demand vertex (subset \( DV \), representing the return point to the river or the lake), connecting vertex (subset \( CV \), representing the point of interconnection of different elements);

- Edges are identified by \( e_j \in E \), where \( j \) is the corresponding index, which represents the material streams and classified as pipes (subset \( PE \), responsible for the transport of water from the source to the condenser and then to return the heated water to the water sink) and heat exchanger tubes (subset \( TE \), that remove heat from the steam).

Therefore, the investigated system is described according to the digraph \( G \) in Figure 2 with a pipe edge \( pe_1 \) representing the distribution header that connects a pumping supply vertex \( v_1 \) to a connecting vertex \( v_2 \) and a pipe edge \( pe_2 \) that leaves the connecting vertex \( v_3 \) to the fixed pressure demand vertex \( v_4 \). The condenser tube side is represented as a set of heat exchanger tube edges \( \{te_1, ..., te_n\} \) between \( v_2 \) and \( v_3 \) vertex.
The state variables of the model are identified according to their corresponding digraph element:

- The vertex state variables are pressure, temperature and external mass flow rate (inlet/outlet of the system).
- The edge state variables are the spatio-temporal distribution of pressure, cooling water temperature, mass flow and the diameter associated to the free flow area.

The specifications of the model were restricted to vertex variables, where the number of required specifications is equal to $|E|$. The vertex model is composed of a mass balance and an energy balance, where the effect of the pressure in the energy balance is neglected.

The edge model is composed of a mass balance, a momentum balance and a heat balance. In this approach, a unique edge model adopted in this paper is employed to represent the behavior of pipes and condenser tubes, unifying the edge representation by the same mathematical structure. In other words, the same model can predict the carbonate deposit formation not only in the condenser tubes but also in the pipe sections.

In order to consider the head loss originated by pipe accidents, the model includes concentrated head losses for edges inlet and outlet. In this context, this approach can be adopted to account for pipe curves, valves, and heat exchanger nozzles and headers.

Each edge has two pressure boundary conditions - that relate the pressure of edge, the pressure of the vertex and the concentrated head loss.

The mass source term was neglected and the momentum source term describes the momentum variation of the fluid related to the viscous shear stress and the gravitational acceleration and is modeled assuming a Darcy friction factor calculated by the Churchill correlation [4].

The heat source term for pipe edges was neglected, and for heat exchanger tubes was calculated according to the model presented in the next Section.

The closure equations describing the physical properties of cooling water, condensate and steam were obtained by the IAPWS Industrial Formulation 1997 correlations.

**Heat Source Term Model**

For $j$-th edge representing a heat exchange tube, the heat source term represents the heat transfer rate from the steam to the cooling water stream and considers internal convection, conduction across the fouling layer and the pipe wall and external convection due to steam condensation. The heat source term is defined as:

$$
\Phi_{T_j} = \frac{T_{V_j} - T_j}{R_I + R_W + R_E + \frac{R_f}{\pi D}}
$$

(1)

Where $T_V$ is the steam temperature, $T$ is the cooling water temperature, $D$ is the tube internal diameter, $R_f$ is the fouling resistance and $R_I$, $R_W$ and $R_E$ are the unitary length thermal resistance for the internal convection, the wall conduction and the external convection.

For the sake of simplicity, we are assuming that tube side flow regime is turbulent, the shell side flow regime is laminar and the internal convection coefficient is obtained by the correlation [5] modified by [6]. The external
convection coefficient considers the effect of the tube position $z$ is calculated by [7]:

$$h_E = \left( z^5/6 - (z - 1)^{5/6} \right) \bar{h}_E$$

where $h_E$ is the heat transfer coefficient for external laminar film condensation of an horizontal isolated tube and is calculated in W/(m$^2$K) based on the correlation [8] adjusted by [9]:

$$h_E(t, x) = 0.729 \left( \frac{g \rho_{Lj}(\rho_{Lj} - \rho_{Vj}) k_{Lj}}{\mu_{Lj}(T_{Vj} - T_{WOj}) D_{WOj}} \right)^{1/4}$$

where $\rho_{Lj}$, $k_{Lj}$ and $\mu_{Lj}$ are the density, the conductivity and the dynamic viscosity of the external condensate film in kg/m$^3$, W/(m·K) and Pa·s, respectively; $T_{Vj}$ and $D_{WOj}$ are temperature and diameter at the tube outer wall in K and m, respectively; $\rho_{Vj}$ is the density of the saturated steam; $\Delta H_{VAP}$ is the vaporization enthalpy in J/kg; and $g$ is the gravitational acceleration in m/s$^2$.

**Fouling Model**

Considering a deposition rate based on Kern and Seaton model [10], it is decomposed into formation $\varphi_d$ and removal $\varphi_r$ rates:

$$\frac{dm_f}{dt} = \varphi_d - \varphi_r$$

where $m_f$ is the mass of deposit per unit of area (kg/m$^2$).

The fouling resistance can be obtained from the mass of the deposit in a circular tube with internal diameter $D$:

$$R_f^* = \log \left( \frac{D}{D - 2m_f/\rho_f} \right) \frac{D}{2k_f}$$

where $R_f^*$ is in m$^2$K/W, $\rho_f$ is the deposit density in kg/m$^3$ and $k_f$ is the thermal conductivity of the deposit in W/(m·K).

The cooling water fouling model adopted in this work focuses on calcium carbonate in the fouling inorganic deposits in a cooling water system was more than 85%.

The deposition rate ($\varphi_d$) in kg/(m$^2$·s) is described by [12] based on Hasson-Quan [13]:

$$\varphi_d = kd [CO_3^{2-}] \frac{1 - k_{sp}[Ca^{2+}][CO_3^{2-}]}{1 + kd k_r [CO_3^{2-}] [Ca^{2+}]}$$

where $k_{sp}$ is the solubility product of CaCO$_3$ at reference temperature and pressure (25°C and 1 atm, respectively), [Ca$^{2+}$] and [CO$_3^{2-}$] are the ionic concentrations, $k_r$ is the precipitation rate (Equation 7) [13] and $kd$ is the transport rate (Equation 8) [13].

$$\ln kr = 38,74 - \frac{20700}{R_g T_w}$$

$$kd = 0,023 u Re^{-0.17} Sc^{-0.67}$$

where $R_g$ is the ideal gas constant in cal/(K·mol); $T$ is the cooling water temperature in K; $u$ is the water velocity in m/s; $Re$ is the Reynolds number; and $Sc$ is the deposit Schmidt number obtained by Equation (9).

$$Sc = \frac{(\mu_w)^2}{3.07 \times 10^{-15} \rho_w T_w}$$

where $\mu_w$ is the water dynamic viscosity in Pa·s, $\rho_w$ is the water density in kg/m$^3$ and $T_w$ is the water temperature in K.

The removal rate ($\varphi_r$) in kg/(m$^2$·s) can be obtained by [12]:

$$\varphi_r = \left( \frac{0,00212 u^2}{k_f^{0.5} \psi} \right) \varphi_d$$

where $\psi$ is the mechanical resistance of the deposition, $k_f$ is the thermal conductivity of the deposit in W/(m·K), and $u$ is the fluid velocity in m/s.

**SIMULATION METHODOLOGY**

The mass, momentum and energy balances partial differential equations...
(PDE) were solved using the center finite difference method available in DAETools [14], a free software released under the GNU General Public License.

RESULTS

The application of the proposed model is illustrated by the simulation of a hypothetical once-through cooling water system including a horizontal condenser with geometry and operational conditions similar to a typical steam power plant, as described in Section Investigated System (Figures 1 and 2 with parameters presented in Tables 1 and 2).

Table 1. Simulation parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Nomenclature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial steam pressure</td>
<td>$P_V(t=0)$</td>
<td>10000 Pa</td>
</tr>
<tr>
<td>Head loss coefficient at $p_e$ outlet</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>Head loss coefficient at $p_e$ inlet</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Head Loss coefficient at each tube inlet</td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>Head Loss coefficient at each tube outlet</td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>Number of mesh points</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Number of tubes in the bundle</td>
<td></td>
<td>34x34</td>
</tr>
<tr>
<td>Pipe length</td>
<td></td>
<td>50 m</td>
</tr>
<tr>
<td>Pipe inner diameter</td>
<td>$D$</td>
<td>0.356 m</td>
</tr>
<tr>
<td>Pipe/tube inclination</td>
<td></td>
<td>0 rad</td>
</tr>
<tr>
<td>Pipe/tube roughness</td>
<td></td>
<td>0.000045 m</td>
</tr>
<tr>
<td>Shell cross section</td>
<td></td>
<td>Square</td>
</tr>
<tr>
<td>Steam volume in the shell</td>
<td></td>
<td>20 m$^3$</td>
</tr>
<tr>
<td>Total heat transfer area</td>
<td></td>
<td>261.51 m$^2$</td>
</tr>
<tr>
<td>Tube bundle layout</td>
<td></td>
<td>Square pitch</td>
</tr>
<tr>
<td>Tube length</td>
<td></td>
<td>4.572 m</td>
</tr>
<tr>
<td>Tube inner diameter</td>
<td>$D_{WI}$</td>
<td>0.0348 m</td>
</tr>
<tr>
<td>Tube outer diameter</td>
<td>$D_{WO}$</td>
<td>0.0381 m</td>
</tr>
<tr>
<td>Tube wall thermal conductivity</td>
<td>$k_W$</td>
<td>50 W/(m$^2$K)</td>
</tr>
<tr>
<td>Condenser steam input</td>
<td></td>
<td>10.95 kg/s</td>
</tr>
<tr>
<td>Water source temperature</td>
<td>$T_1$</td>
<td>286.95 K</td>
</tr>
</tbody>
</table>

Table 2. Parameters for the fouling model

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical resistance ($\psi$)</td>
<td>0.01</td>
</tr>
<tr>
<td>Deposit thermal conductivity ($k_d$)</td>
<td>2.941 W/m K</td>
</tr>
<tr>
<td>Density of CaCO$_3$ deposit ($\rho_f$)</td>
<td>2710 kg/m$^3$</td>
</tr>
<tr>
<td>Solubility product (ksp)</td>
<td>4.9E-9 mol/L$^2$</td>
</tr>
<tr>
<td>Molar fraction of CO$_2$ in air</td>
<td>3.14E-4</td>
</tr>
<tr>
<td>pH</td>
<td>9.55</td>
</tr>
<tr>
<td>Ca$^+$ concentration</td>
<td>1.2 mmol/L</td>
</tr>
</tbody>
</table>

The vertex $v_1$ is modeled as a pumping supply vertex with pump curve corresponding to a polynomial with the following coefficients equal to 276935 Pa, 0 Pa/(kg/s) and -0.1865 Pa/(kg/s)$^2$. The vertex $v_4$ is modeled as a fixed pressure demand vertex with pressure equal to $10^5$ Pa.

For the sake of simplicity, the determination of ionic specimen concentrations in Equation 6 is not covered in this paper, but they can be obtained based on the pH, the molar fraction of carbon dioxide in air, the calcium cation concentration in Table 2 and dissociation equilibrium and Henry equilibrium equations [16].

In Figures 3-13, the dynamic simulation of the proposed model with and without fouling are compared. The initial condition considers the initial steam pressure defined in Table 1 and the solution of the steady state model forcing null value for the time derivative terms.

By starting our analysis with the steam quality, we can observe that there is an increase in the steam pressure over time (Figure 3). The fouling caused an increase in the backpressure of the steam turbine. Although this work does not include the turbine modelling, it is clearly recognized that a higher backpressure will reduce the turbine power.

Fig. 3. Shell steam pressure

Nevertheless, we can observe that there is a secondary effect that is relevant to the heat exchange phenomena, that corresponds to the main reason to adopting a process system approach. If we assume that the It corresponds to an increase in the steam temperature caused by the
achievement of a different equilibrium point in the shell side (Figure 4).

Now that we discussed the secondary effects, we can focus the analysis on the cooling water temperature. It is important to remember that our model uses distributed parameters along the tube axial position $x$, and also considers the tube vertical position inside the tube bundle ($z=1$ is the top position and $z=34$ is the lower position for this system).

In Figure 7, the temperature of cooling water at the outlet of a tube in the top position ($z=1$) reduces with time. Between days 720 and 770, the numerical solver produced numerical oscillations that are not expected in the modeled phenomena, but are explained by the complexity of the mathematical model and its integration over a very long time horizon.

Fig. 4. Shell steam temperature

Another aspect that reinforces the necessity of considering the hydraulic system and not the isolated heat exchanger is the cooling water flowrate reduction over time (Figure 5).

Fig. 5. Cooling water flowrate

The increase in the fouling deposit implies a reduction of the free flow area. The temporary larger flow velocity (Figure 6) - with corresponding increase in head loss - causes the system to shift to a new operational point in terms of system head loss and pump head curve.

Fig. 6. Fluid velocity (mean value of the different $z$ positions)

Nevertheless, Figure 8 shows that the temperature at the outlet of a tube in the lower position ($z=34$) increases with time.

Fig. 7. Water temperature at tube outlet ($z=1$)

Fig. 8. Water temperature at tube outlet ($z=34$)

The same analysis can be observed for the profiles of cooling water temperature along the axial position as in Figure 9.
The fouling resistance increases with time and after 5 years of operation becomes about $0.21 \cdot 10^{-3} \text{ m}^2\text{K}/\text{W}$ for the tube at $z=1$ (Figure 10) and $0.19 \cdot 10^{-3} \text{ m}^2\text{K}/\text{W}$ for tube at $z=34$ (Figure 11). The profiles in Figure 12 indicates that the tube inlet presents a fouling resistance that is about 20% lower than the tube outlet.

Finally, we can observe the overall heat load of the condenser in Figure 13, where the total heat load of the system decreases due to the pressure dependence of the heat of vaporization.
CONCLUSION

The proposed model was able to describe the system of interest, where different complex phenomena occur and compete.

The classic adoption of rules of thumb with stationary fouling factor is a common engineering practice and is valid for different applications. Nevertheless, the adoption of a process systems approach, represented by a graph based model, can give better insights (especially when the interaction between the elements implies in competitive feedbacks).

An accurate model of the power plant cooling systems under fouling phenomena can give better insights and a more detailed description of the operational behavior of the equipment [15].

NOMENCLATURE

List all symbols used within the manuscript, their definitions, and their SI units.

\( \rho \)  
Density, \( \text{kg/m}^3 \)

\( \mu \)  
Dynamic viscosity, \( \text{Pa s} \)

\( \phi_d \)  
Deposit formation rate, \( \text{kg/s} \)

\( \phi_r \)  
Deposit removal rate, \( \text{kg/s} \)

\( \Phi_T \)  
Heat source term, \( \text{W/m} \)

\( [X] \)  
Concentration of ion \( X \), \( \text{mol/L} \)

\( cv \)  
Connecting vertex element

\( CV \)  
Connecting vertice set

\( dv \)  
Demand vertex element

\( DV \)  
Demand vertice set

\( e \)  
Edge element

\( E \)  
Edge set

\( G \)  
Graph

\( H \)  
Enthalpy, \( \text{J/kg} \)

\( h \)  
Heat transfer coefficient, \( \text{W/(m}^2\text{K}) \)

\( kd \)  
Transport coefficient

\( kr \)  
Precipitation rate coefficient

\( ksp \)  
Solubility product of CaCO\(_3\), \( \text{mol}^2/\text{L}^2 \)

\( m \)  
Mass of deposit per area, \( \text{kg/m}^2 \)

\( pe \)  
Pipe edge element

\( PE \)  
Pipe edge set

\( R \)  
Thermal resistance per length, \( \text{mK/W} \)

\( R^\prime \)  
Fouling resistance, \( \text{m}^2\text{K/W} \)

\( Re \)  
Reynolds number

\( Sc \)  
Schmidt number

\( sv \)  
Supply vertex element

\( SV \)  
Supply vertice set

\( T \)  
Temperature, \( \text{K} \)

\( te \)  
Heat exchange tube element

\( TE \)  
Heat exchange tube set

\( u \)  
Velocity, \( \text{m/s} \)

\( v \)  
Vertex element

\( V \)  
Vertex set

\( VAP \)  
Vaporization

\( z \)  
Tube position

Subscript

\( E \)  
External

\( f \)  
Fouling or deposit

\( I \)  
Internal

\( i \)  
Vertex index
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