Methodology for generic pipe model: Failure risks assessment for heating and
domestic hot water systems due to corrosion and bacterial growth

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Abstract

Both water supply systems as district heating grids, drain or sewer systems exist out of complex networks of water pipes and channels. Different types of threats or water pollution can be distinguished on system level, such as corrosion and bacterial growth. These threats are often strongly linked to each other, as there is a clear correlation between some threats regarding growth and propagation in networks.

This paper proposes a generic modelling approach to describe the growth and propagation of corrosion and bacterial growth threats in water networks. The model is based on a two control volumes approach for each threat, namely a flow conducting volume and a layer volume. The double control volume approach allows to include the specific behavior in biofilm, convection layer, pipe surface, … with respect to growth, diffusion and decline of each threat. This occurs at different speed compared to the main water volume. By including an exchange between both layers within the water pipe model, the model can take this into account and still be easily incorporated in large system assemblies. The result is a better understanding of the failures or a comprehensive base for data interpretation, which is a first step adopting machine-learning techniques in this field for predictive maintenance.

1- Introduction

With civilization, transport of water through ducts and pipes has numerous applications. They show up in water distribution networks supplying water for washing and hygienic purposes [1]. The lack of water is still one the main problems resulting in poor living conditions, poverty and migration [2]. This illustrates the importance, despite its common nature. Also in heating and cooling systems, the use of water pipes to transport heat from heater to radiator within a building or throughout an entire city by a district heating network. Besides the provision of heat and water, both for domestic as for industrial applications, water is often used as a carrier to remove waste or other materials through sewers and other utilities. Because of the aforementioned reasons, the hydraulic behavior of water through pipes is one of the oldest research domains within fluid dynamics, enabling proper design and control (Study [3] in 1995).

When exposed in aquatic environment, materials suffer from corrosion influenced by physical, chemical and biological parameters. Among these, microbiologically influenced corrosion (MIC) has received much more attention these years where it has been estimated to account for 20% of annual corrosion damage of metallic materials [4,5]. The corrosion of pipes is not only responsible for the destruction of the pipe material, but also for the deterioration of water quality. Corrosion scales formed by the accumulation of corrosion products can reduce the water transportation capacity and offer habitation for pathogenic and opportunistic bacteria [6,7], red water or discolored water that caused by severe corrosion product release are among the main reasons for consumer complaints. On the other hand, and as an example, the drinking water systems can be considered as a large-scale biological environment that hosts a wide variety of microorganisms both in bulk water and on the pipe surfaces (as biofilms), which could lead to high disinfectant demand and dissolved oxygen (DO) consumption [8].

1.1. Literature review

On each aspect, different studies exist. In [9], the influence of oxygen and flow conditions on the iron deterioration and formation of magnetite or other corrosion products have been investigated. In [10] and [11] the influence of water
quality and presence of other dissolved gases on corrosion rate is studied, whereas other studies focus on the improvement of corrosion resistance of the pipe material itself [12]. As the presence of oxygen influences corrosion, the presence of air infiltration is strongly linked to corrosion phenomena. Typically, under pressure (below atmospheric conditions) is a known trigger to increase the diffusion of air into the water pipe. In [13], the diffusion of air through polypropylene pipes is investigated, whereas [14], [15] and [16] describe the transport of these gas (droplets) through the pipes, not only locally, but also along with the flow of water. Similar remarks can be made for bacterial growth, which can happen at different locations, but do influence each other as presented in [17] on a system level.

Van Kenhove on Legionella [18], presents a modelling approach that combines a hydraulic pipe model with the risk on Legionella decontamination. The pipe model exists out of two control volumes, namely water and biomass. For each control volume, empirical models describe Legionella growth/starvation. The model is bound to some assumptions, that need more careful interpretation, and limit the applicability of the model.

1.2. Summary and problem statement

Bacteria and corrosion lead to failures or pollution in water networks. They cannot be treated separately, as there is a clear correlation between them. To examine that, one should understand not only their origin, growth or decline, but also how the products of these threats propagate through the network. For this reason, this paper proposes a methodology for a generic pipe model, which can predict the different threats and to describe how their product is transferred through the network.

2- Theory and Hypothesis

2.1. Theory

Water systems are composed of different components, such as pipes, heat sources, storage tanks, heat exchangers, expansion vessels and taps. Therefore, system component models have to be updated with corrosion, bacteria and correlative growth equations. Figure 1 illustrates the principle of implementation of mass transfer equations with respect to assumed control volumes within a portion of pipe. In this way, the propagation of the corrosion products and bacterial biofilm within the water system can be simulated, evaluated and consequently predicted.

Figure 1: Pipe portion with two control volumes, local layer and bulk. Implementation of mass transfer equations

2.2. Hypothesis

In literature, there are no previous attempts to model the correlation of bacterial growth and corrosion in pipes with water as working fluid. The found literature focused on modelling the threats separately and with particular cases of bacteria such as Legionella pneumophila in [18] and Iron corrosion in [19]. The authors supposed that found bacterial growth and corrosion equations can be turned into generic equations fit with the bacteria types, corrosion products, and pipe materials.

3- Methodology

As done in [18], different existing Modelica pipe models can be analyzed to select useful model that could be extended with equations for simulation of bacterial growth and corrosion. After selecting useful pipe model, component models are chosen to be the first to be adapted with the implementation of the threats, as growth and exchange take mainly place in these components using Dymola. Figure 2 shows the proposed methodology and the expected results.
The benefit of modelling the threats’ growth in an existing pipe component model is the ease of compiling simulation models of different systems later by dragging and dropping different components (which already include bacterial growth and corrosion equations) into the system model.

Figure 2: The proposed methodology and expected results

3.3. Pipe model selection

There are number of parameters necessary for modelling bacterial and corrosion growth. The parameters are divided into three categories, namely the three conservation equations: Mass, Momentum and Energy.

- The mass conservation parameter (trace substances) indicates if the existing pipe component contains certain flow equations that make it possible to add substances to water.
- Momentum conservation parameter (gravity) defines if the pipe can be used in all directions (vertical/horizontal). A pipe model without inclusion of gravity can only be used horizontally, except if the gravity equation is canceled by the pressure drop.
- Energy conservation parameters, for example the possibility to add a (heat source) and (insulation), are meaningful parameters to take into account.

Existing pipe models can be compared based on the above parameters necessary for modelling bacterial and corrosion growth and that may or may not have been considered in the conservation equations in the existing component models, so by comparing these parameters, the existing pipe models that can be extended with equations for simulation of threats growth in water system

3.2. Implementation of equations

3.2.1. Mass transfer equations of bacteria

Bacteria may grow across a wide range of temperatures, from very cold to very hot, while it grow to a fixed size and then reproduce through binary fission [20]. Bacteria have a minimum, optimum, and maximum temperatures for growth and can be divided into 3 groups based on their optimum growth temperature: Psychrophiles are cold-living bacteria (-5 to 15°C). The Mesophiles are bacteria that grow best at moderate temperatures with optimum growth temperature is between 25°C and 45°C and finally the Hyperthermophiles are bacteria that grow at very high temperatures (70 to 110°C). In this paper, Mesophiles are represented as “the average bacteria” that can be modelled due to the optimum temperature range that match with the average temperature range in the water network and storage systems, and as mentioned in the hypothesis, the Legionella pneumophila is considered as the average mesophile. Multiplication of L. pneumophila is dependent on water temperature, volume flow rate, flow frequency, followed by
To model *L. pneumophila* growth in water in a pipe, equations need to be added to the hydraulic model. Following mass conservation equations, that predict *L. pneumophila* growth in water, need to be coupled to an existing pipe component [18] (equations below).

\[
V_p \frac{dC(t)}{dt} = Cin(t) \cdot \frac{Qin(t)}{\rho} - Cout(t) \cdot \frac{Qout(t)}{\rho} + \text{growth in water} + \text{mass transfer between water and biofilm}
\]

\[
= V_p \frac{dC(t)}{dt} = Cin(t) \cdot Ain(t) - Cout(t) \cdot Aout(t) + Vp \cdot m(t) + k_c \cdot A_b \cdot (C_b(t) - C(t))
\]

Eq. 1

\[
Qin(t) = Qout(t)
\]

Eq. 2

\[
m(t) = C_{\text{previous}} \cdot \frac{\ln(2)}{y} \cdot e^{-\frac{\ln(2) \cdot dt}{y}}
\]

Eq. 3

To model *L. pneumophila* growth in biofilm in a pipe, equations need to be added to the hydraulic model in a similar way as for growth in water. Following mass conservation equations, that predict *L. pneumophila* growth in the biofilm, need to be coupled to an existing pipe component.

\[
V_b \frac{dC_b(t)}{dt} = C_b,\text{in}(t) \cdot \frac{Q_b,\text{in}(t)}{\rho} - C_b,\text{out}(t) \cdot \frac{Q_b,\text{out}(t)}{\rho} + \text{growth in biofilm} + \text{mass transfer between water and biofilm}
\]

\[
= V_b \frac{dC_b(t)}{dt} = C_b,\text{in}(t) \cdot Ab,\text{in}(t) - C_b,\text{out}(t) \cdot Ab,\text{out}(t) + Vb \cdot mb(t) + k_c \cdot A_b \cdot (C(t) - C_b(t))
\]

Eq. 4

\[
Qin(t) = Qout(t) = 0
\]

Eq. 5

\[
mb(t) = C_b,\text{previous} \cdot \frac{\ln(2)}{y_b} \cdot e^{-\frac{\ln(2) \cdot dt}{y_b}}
\]

Eq. 6

Where,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_b$</td>
<td>[m²]</td>
<td>Surface between water and biofilm</td>
</tr>
<tr>
<td>$C(t)_{\text{and}}$ $C_b(t)$</td>
<td>[cfu/m³]</td>
<td>Concentration of <em>L. pneumophila</em> in water and biofilm respectively at time t</td>
</tr>
<tr>
<td>$Cin(t)$ and $Cout(t)$</td>
<td>[cfu/m³]</td>
<td>Concentration of <em>L. pneumophila</em> in water entering and leaving system respectively</td>
</tr>
<tr>
<td>$C_{\text{previous}}$ and $C_b,\text{previous}$</td>
<td>[cfu/m³]</td>
<td>Concentration of <em>L. pneumophila</em> in water and biofilm respectively on previous timestep.</td>
</tr>
<tr>
<td>$\frac{dC(t)}{dt}$ and $\frac{dC_b(t)}{dt}$</td>
<td>[cfu/m³·s]</td>
<td>Changing concentration of <em>L. pneumophila</em> over time in water and biofilm respectively</td>
</tr>
<tr>
<td>$k_c$</td>
<td>[m/s]</td>
<td>Mass transfer coefficient to calculate the mass transfer of <em>L. pneumophila</em> between water and biofilm</td>
</tr>
<tr>
<td>$m(t)$ and $mb(t)$</td>
<td>[cfu/m³·s]</td>
<td>Change in concentration of <em>L. pneumophila</em> in water and biofilm respectively due to growth or death</td>
</tr>
<tr>
<td>$Qin(t)$ and $Qout(t)$</td>
<td>[kg/s]</td>
<td>Mass flow rate of water (containing <em>L. pneumophila</em>) entering and leaving system respectively</td>
</tr>
</tbody>
</table>
3.2.2. Mass transfer equations of corrosion

It has been previously suggested that, in the mathematical simulation of the corrosion of steels in neutral solutions, at least six species in the solution must be taken into account [23]. These species are the metal “Me” (e.g. Fe or Cu) ions from the dissolution process, sodium and chloride ions (for example), which are commonly included to control the bulk conductivity, hydrogen and hydroxyl ions from the dissociation of water, and a metal hydrolysis product e.g. Fe(OH)²⁺ in neutral solutions, at pH ≈ 7. In their investigation, Engelhard et al. [24], assumed that dissolved oxygen is also present in the solution and, accordingly, it is assumed that there are seven different species, S_j (j=1,2,3,…7), inside and outside the cavity, so that the followed approach will be adopted.

\[ S_1=\text{Me}^{2+}, \quad S_2=\text{Me(OH)}^+, \quad S_3=\text{Na}^+, \quad S_4=\text{Cl}^-, \quad S_5=\text{H}^+, \quad S_6=\text{OH}^-, \quad S_7=\text{O}_2 \]

With the volume-based concentrations being designated as, C_j (mol/cm³). If the rates of the chemical reactions are sufficiently high, the concentrations of the species can be set equal to their equilibrium values with the equilibrium constants K_1, K_2, and K_w being defined as:

\[ K_1=\frac{C_2C_3}{C_1}, \quad K_2=\frac{C_3}{C_2}, \quad K_w=\frac{C_4C_6}{C_5} \]

where the activity coefficients are assumed to be unity, as are the standard state concentrations. The boundary conditions far from the crevice mouth at (x → -∞) are written as

\[ C_1=C_2C_3/K_1, \quad C_2=C_3/K_2, \quad C_3=C_{\text{NaCl, water}}, \quad C_4=2C_1+C_2+C_3+C_5+C_6, \quad C_5=10^{-pH_{\text{water}}}, \quad C_6=K_{\text{water}}/C_5, \quad C_7=0=C_{\text{O}_2, \text{water}} \]

\( pH_{\text{water}} \) is the bulk value of the pH and \( C_{\text{NaCl, water}} \) and \( C_7 \) are the bulk concentrations of NaCl and O₂, respectively. Corrosion formation can be subdivided in five different processes: electrochemical reactions, chemical reactions, flux, diffusion and electromigration. The main chemical reactions that occur include the hydrolysis of metal II ion, precipitation of metal II hydroxide and water dissociation. Equations for these reactions are:

- \( \text{Me}^{2+} + \text{H}_2\text{O} \leftrightarrow \text{Me(OH)}^+ + \text{H}^+ \)
- \( \text{Me(OH)}^+ + \text{H}_2\text{O} \leftrightarrow \text{Me(OH)}_{2(\text{ss})} + \text{H}^+ \)
- \( \text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{OH}^- \)

Concentration variations at the interface, which are governed by the chemical reactions mentioned, must also meet the mass conservation equation, which includes the transport of species. The general equation describing the transport of species j, including the contribution of chemical reactions and the electrostatic potential is [19]:

\[ \frac{\partial c_j}{\partial t} = \nu^*(t) \frac{\partial}{\partial x} \left( \nu(x) \frac{\partial c_j}{\partial x} + \frac{nF}{RT} c_j \frac{\partial \varphi}{\partial x} \right) + w \frac{dc_{Rj}}{dt} | \text{chemical reaction} \]
where \( x \) is the spatial coordinate representing the distance from the edge of the crevice, \( w \) is the crevice width, \( D_j \) is the molecular diffusion coefficient, \( \varphi \) is the electrostatic potential at the deep of the crack.

### 4- Conclusion and future recommendations

The different threats leading to failures or pollution in water networks cannot be treated separately, as there is a clear correlation between them, so for the further steps, the correlation in the growth and death of corrosion and bacterial growth can be studied. To examine the different kind of threats, one should understand not only their origin, growth or decline but also how the result of these threats propagates through the network.

### 5- References