Influence of Limescale on Heating Elements Efficiency

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Introduction

Electric resistances are widely used as heating elements in domestic and industrial equipment; since process water contains calcium carbonate and calcium bicarbonate, limescale plays an important role on global efficiency of water-heating systems.
Limescale is caused by the equilibrium between dissolved calcium bicarbonate and dissolved calcium carbonate:

$$Ca^{2+} + 2HCO_3^{-} \leftrightharpoons Ca^{2+} + CO_3^{2-} + CO_{2(dis)} + H_2O$$

Carbon dioxide dissolved in water is in equilibrium with that in the gaseous state (g):

$$CO_{2(dis)} \leftrightharpoons CO_{2(g)}$$

When the temperature rises, CO_2 equilibrium moves towards the gas phase and, as a consequence, the equilibrium of calcium carbonate shift to the right; as the concentration of carbonate increases, calcium carbonate precipitates:

$$Ca^{2+} + CO_3^{2-} \leftrightharpoons CaCO_3$$

Calcium carbonate has a very low thermal conductivity (2.2 W/(m*K) and the carbonate deposit on the heating element causes a decrease of the overall heat transfer coefficient and consequently a reduction of the system efficiency.

Computational Methods

In order to analyze the effect of the carbonate layer on the heat transfer process, a 2D-axisymmetric model of a tubular heat-exchanger has been simulated with COMSOL Multiphysics; an inlet water velocity of 1m/s, an electric potential of 230V (the resulting power is about 2kW) and a variable thickness layer of $CaCO_3$ are used as input (Figure 1). The water volume in the system is 10 liters. Thus the resulting specific power is 200W/l and the residence time is equal to 0.8s. Water at the exit is recirculated at the inlet.

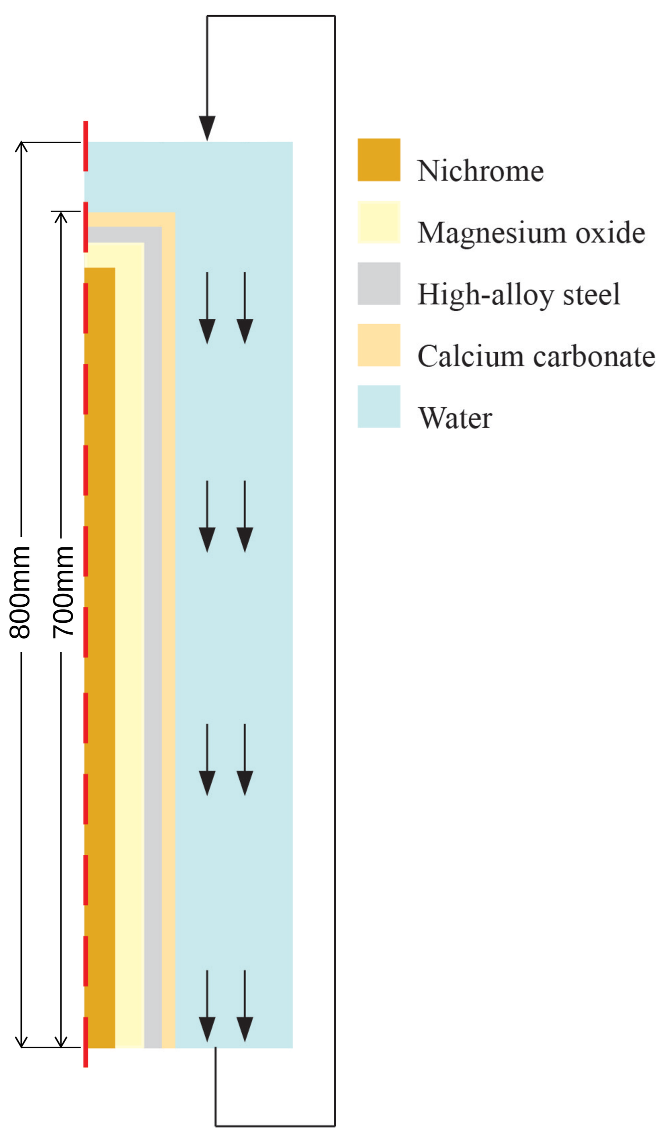

Figure 1. Geometry of the system.

Two different physics were used:

- The Joule Heating Interface, to simulate joule heating effect and the heat transfer phenomena.
- The turbulent flow interface, with a k-ε model, to simulate the fluid flow in a closed loop.

In the Nichrome domain the following equations apply:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla(k \nabla T) = Q \qquad (1)$$

$$Q = J \cdot E \qquad (2)$$

In the magnesium oxide, steel and carbonate domains the same equations were used with Q=0 (no internal heat generation).

In the fluid domain the heat equation is given by:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T = \nabla(k \nabla T) \qquad (3)$$

To simulate the fluid flow two different equations were used, one for the turbulent kinetic energy (k) and one for the dissipation rate of turbulence energy (ε):

$$\rho \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right) + P_k - \rho \varepsilon \qquad (4)$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho u \cdot \nabla \varepsilon = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \qquad (5)$$

Results

The average liquid temperature trends at different limescale thickness are reported in Figure 2; the graph shows a liquid temperature decrease of 5ºC for a 2mm limescale thickness after 480 seconds (time to reach a final liquid temperature of 60ºC without limescale).
Figure 3 shows the average heating element temperatures at different limescale thickness; in this graph is it is shown that limescale causes a relevant increase of the internal temperature of the heating element. For example for a limescale thickness of 2mm the temperature increase of the heating element is equal to 43ºC.
The heating power as a function of time is reported in Figure 4; as it can be seen limescale causes a relevant decrease on heating power, due to the resistivity dependence on temperature.
Figure 5 reports the temperature profile in a cross-section of the system under investigation at 480s; the graph shows that, despite the relevant increase in the heating element temperature, the water temperature in presence of limescale is lower in presence of limescale; this is due to the very low thermal conductivity of the $CaCO_3$.

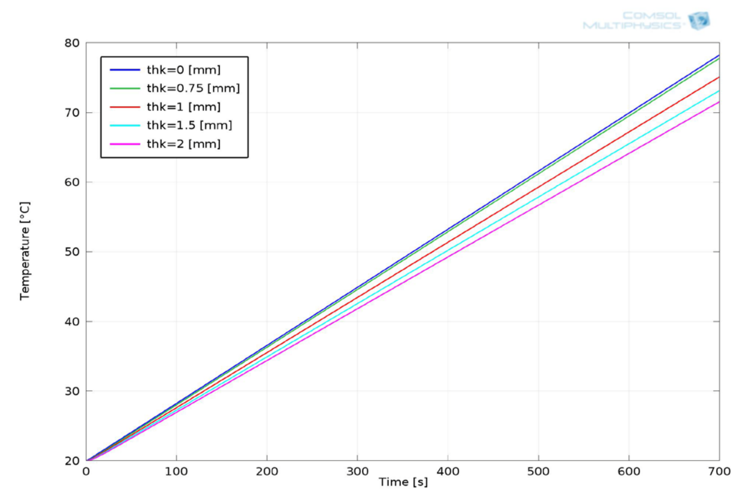

Figure 2. Average liquid temperature.

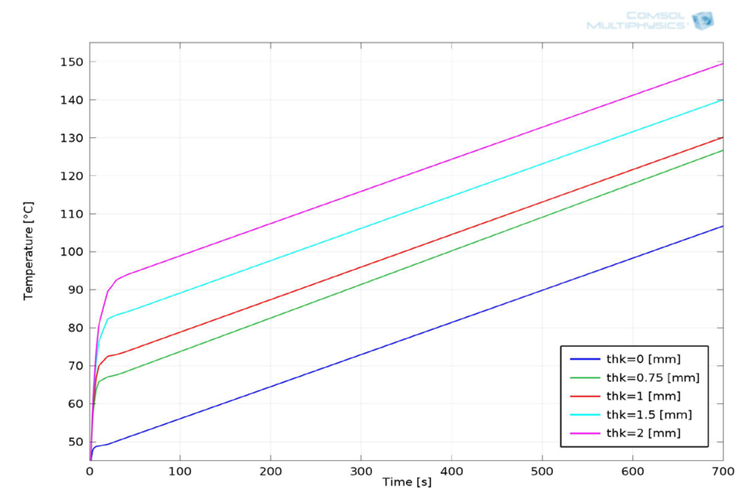

Figure 3. Average heating element temperature.

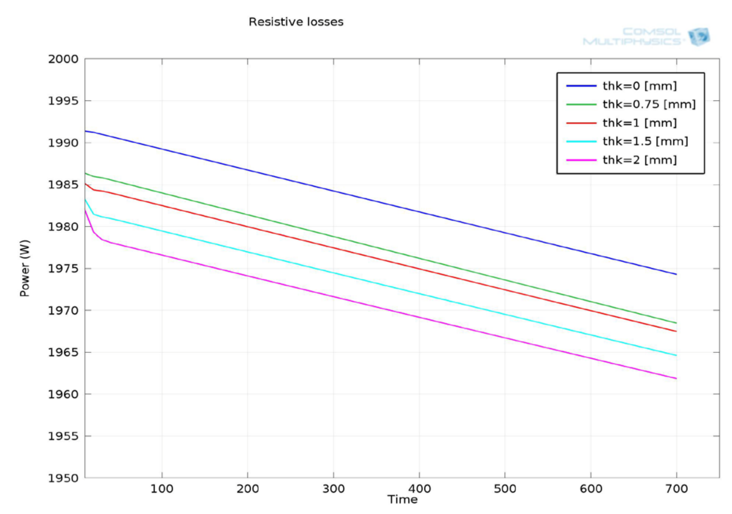

Figure 4. Heating power.

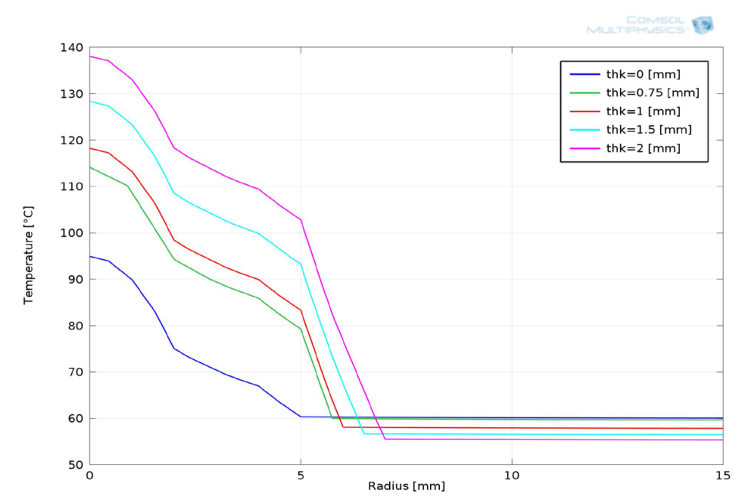

Figure 5. Temperature profile in a cross-section at 480s.

The energy consumptions at different limescale thickness were calculated and for a 2mm limescale thickness the increasing in consumption is about 12.5%.
In order to analyze only the effect of the limescale, some simulations with constant heating power were done and the resulting increase in energy consumption is about 12.3%; this leads to conclude that the increasing in energy consumption is due only to limescale.

Conclusion

Limescale plays an important role on the efficiency of a heating system because it increases the process time and the energy consumption to achieve the same results.
Assuming that our system is a simplified model of a washing machine heating system and considering a washing cycle at 60ºC, the heating time increase of about 64s in the case of a 2mm limescale thickness; assuming that every family in Italy has a washing machine, for every cycle the increase in energy consumption is about 75.8toe (1toe = 11.36 MWh).

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