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:

\[ \text{Ca}^{2+} + 2\text{HCO}_3^- \rightleftharpoons \text{CaCO}_3 + 2\text{CO}_2 + \text{H}_2\text{O} \]

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

\[ \text{CO}_2(g) \rightleftharpoons \text{CO}_2(l) \]

When the temperature rises, CO2 equilibrium moves towards the gas phase and, as a consequence, the equilibrium of calcium carbonate shifts to the right; as the concentration of carbonate increases, calcium carbonate precipitates:

\[ \text{Ca}^{2+} + \text{CO}_3^- \rightleftharpoons \text{CaCO}_3 \]

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 CaCO3 are used as input (Figure 1). The water volume in the system is 10 liters. Thus the resulting specific power is 200W and the residence time is equal to 0.8s. Water at the exit is recirculated at the inlet.

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:

\[ \rho C_v \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \]  
\[ Q = J \cdot E \]  

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:

\[ \rho C_v \frac{\partial T}{\partial t} + \rho C_\mu \nabla T = \nabla \cdot (k \nabla T) \]  

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):

\[ \frac{\partial k}{\partial t} + \rho \mathbf{u} \cdot \nabla k = \nabla \cdot \left( \frac{\mu + \mu_s}{\sigma_k} \nabla k \right) + P_k - \rho \varepsilon \]  
\[ \frac{\partial \varepsilon}{\partial t} + \rho \mathbf{u} \cdot \nabla \varepsilon = \nabla \cdot \left( \frac{\mu + \mu_s}{\sigma_\varepsilon} \nabla \varepsilon \right) + C_{\mu} \frac{\varepsilon}{k} P_k - C_{\varepsilon} \varepsilon \frac{\varepsilon^2}{k} \]  

The energy consumptions at different limescale thickness were calculated and for a 2mm limescale thickness the increasing in consumption is about 12.9%. 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 60°C, 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).

References


Acknowledgements

The authors thank Prof. Rainer Stamminger for his scientific contribution.