Numerical Simulation of Fluid Flow and Heat Transfer in a Water Heater

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Abstract: - Energy consumption represents a major concern, considering the limited resources and latest targets for lower emissions of carbon dioxide. Therefore design of electric heating elements for household and industry are more and more subject to optimization, in order to improve efficiency and minimize losses. An analysis has been made using the finite elements method to optimize the efficiency of an instant electric heater used for production of hot water. The actual solution is used now for a large scale production of heaters, and is based on considerable and mostly empirical experience. However some problems have been reported during exploitation and maintenance of industrial equipment provided with hot water by such instant heaters. Some new technical solutions have been analyzed to improve the classic design. Optimized solutions have been based on simulation of heat transfer and water flowing for some constructive solutions: different positions of heating element, water inlet or outlet, as well as a new form of heating element. Calculations have been formulated in order to determine distribution of temperature in heated water and on surface of heating element. Temperature distributions indicate that the new shape of heating element is likely to improve both heating efficiency and reduce occurrence of failures.

Key-Words: - Heat transfer, Fluid flow, Electric heating, Finite elements

1 Introduction
Latest concerns for reducing of greenhouse gas emissions, considered the main reason responsible for anthropogenic global warming have boosted up both technical and managerial efforts of industrial companies worldwide. If industrial and household heating is concerned there are some evident directions to eliminate direct carbon dioxide emissions on which technical research and development are focused:
- Replacement of heating technologies based on burning of fossil fuel with different methods of electric heating;
- Optimization of heating efficiency based on electric energy, in order to reduce losses and specific consumptions;
It is well known that production of electric energy is still based in many cases on burning of fossil sources (coal, gas, oil), and is also producing carbon dioxide emissions.
However it may be considered that fuel burning is more efficient in power plants, which could more easily adopt environment-friendly technologies. On the other hand consumption of electric energy will virtually benefit from all improvements implemented in electricity production, and their positive effects will propagate to all industrial processes that use electric energy instead of burning fossil fuel.
Although electric energy has been considered for many years to be cheap and inexhaustible, increased energy prices and environmental consciousness have triggered considerable efforts to improve product design, for better performances and durability, especially when large scale production is involved.
2 Parameters of instant water heater

A typical electric heater, which is subject to optimization, is composed of a stainless steel container (figure 1) and an electric heater (figure 2). The water is provided by mean of an inlet orifice, heated during the contact with the surface of heating element, and expelled through the outlet orifice. The heater is calculated to heat a quantity of 1 liter of water/minute, i.e. 0.017 liters/second or 60 liters of water every hour. The average temperature of the heated water should be between 60 and 70°C.

The heater is provided with an electric heating element, which supplies a net heating power of 3500 W. The heating elements consist of a helical Ni-based resistive wire, an isolation of magnesium oxide powder and an exterior protection tube of INCOLOY 800 (figure 3).

The main parameters of heating regime are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water mass flow [kg/s]</td>
<td>0.017</td>
</tr>
<tr>
<td>Voltage on heating element [V]</td>
<td>240</td>
</tr>
<tr>
<td>Thermal power [W]</td>
<td>3500</td>
</tr>
<tr>
<td>Max. fluid temperature range [°C]</td>
<td>60±3</td>
</tr>
<tr>
<td>Min. fluid temperature range [°C]</td>
<td>70±3</td>
</tr>
<tr>
<td>Max. temperature on heating element [°C]</td>
<td>900</td>
</tr>
</tbody>
</table>

3 Analysis conditions

Considering the relatively complex configuration of heater, and the possible complicated flowing trajectories, it was decided an analysis on a three-dimensional model. The simplified solid analyzed using the Flow Simulation software is presented in figure 4.

The most importance boundary conditions applied to the model are:
- the calculation model is limited to the exterior limits of the container, and only the interior flowing of the fluid is simulated, both for laminar and turbulent flowing;
- water inlet is constrained to a mass flow rate of 0.017 kg/s;
- water outlet is constrained by a static pressure of 101325 Pa;
- heat conduction in solids is considered, as well as natural convection in air on the exterior of container (20 W/m² °C)

Heating power of 3500 W is considered uniformly distributed on the surface of heating element.
The classic design has been evaluated to be satisfactory in terms of heating capacity and dimensions. However, maintenance information suggests relatively frequent failure of heating elements, probably as consequence of overheating. There are also some doubts related with the thermal uniformity of the outcoming water. Since configuration of the heater is based on company experience and good practice, numerical analysis could give precious information for higher efficiency.

4 Analysis of flowing and heat transfer
Design optimization is based on simulation of fluid flowing inside container and heat transfer between heating element and fluid.
A number of 4 different cases that cover practically all possibilities of use for the heater have been considered, as follows:
1. The plane of heating element is perpendicular with the lateral orifice (as presented by figure 4), which represents the water inlet; water outlet is on the bottom of container (case no. 1);
This case also represents the actual construction, which is presently used for large scale fabrication of heaters;
2. Same orientation of the plane of heating element, but water inlet is on the bottom and outlet is on the lateral (case no. 2);
3. The plane of heating element is parallel with the axis of lateral orifice, which is also the water inlet; water outlet is on the bottom (case no. 3);
4. Same orientation of heating element, with water inlet on the bottom and outlet in lateral (case no. 4);
The thermal fields of the water content have been determined in two different vertical sections. These distributions for case no. 1 are presented together with surface temperature distribution on the heating element in figure 5.
There is also of practical interest to determine temperature variation along the diameter of the outlet orifice, since this distribution is actually determining the output of the heater. This particular variation is presented in figure 6.
The result of water heating could be considered satisfactory, since fluid leaves container at a temperature that comply with the generally requirements, i.e. between 60 and 70°C. However water has the highest temperature inside the container and not at exit, which does not assure optimum efficiency.

On the other hand, heating element is not symmetrically loaded, and has an area were temperature is close to 900°C, which is the upper limit of working range, and could be responsible for early failure and reduced durability, as reported in some cases.

If bottom orifice is used as water inlet (figure 7), as occasionally could happened, if an incorrect assembly is made, the maximum fluid temperature is lower, and water temperature at exit is toward the lower limit, although the gradient is smaller (figure 8).

The maximum temperature on the heating element is even closer to the 900°C limit, which also endangers durability.

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**Fig. 6.** Variation of water temperature on the outlet for case no.1.

**Fig. 7.** Distribution of temperature for case no.2

**Fig. 8.** Variation of water temperature on the outlet for case no.2.
Fig. 9. General appearance of the three-dimensional model for case no. 3 and 4.

(a) fluid temperature through front vertical section.
(b) fluid temperature through lateral vertical section.
(c) solid temperature through lateral vertical section.

Fig. 10. Distribution of temperature for case no. 3

Fig. 11. Variation of water temperature on the outlet for case no. 3.

Modifying the position of heating element relative to the lateral orifice of container, is also changing conditions for fluid flowing and heat transfer (figure 9).
4 Solution optimization

There are some evident flaws that have been determined by numerical simulation of electric heaters. Therefore a separate study has been pursued to determine an optimized solution.

In this respect a new simulation has been conceived for a new form of helical electric heater, currently used for other applications. The analysis has been made for both lateral and bottom position of water inlet. The general appearance of the modified model is presented in figure 14.

![Fig. 14. General appearance of the modified three-dimensional model.](image)

An analysis of the temperature distribution of fluid inside container (figure 15 a, b) reveals that difference between maximum and minimum level is significantly smaller, without any isolated area where water is very hot.

![Fig. 13. Variation of water temperature on the outlet for case no.4.](image)

(a) fluid temperature through front vertical section.

(b) fluid temperature through lateral vertical section.

(c) solid temperature through front lateral section.

Fig. 12. Distribution of temperature for case no.4

Fig. 13. Distribution of temperature for case no.4
The most important benefit of the new solution consists in the maximum temperature of the heating element, which is considerably lower in comparison with the classic solution, i.e. under 300°C. This would probably reduce considerably the thermal load and increase durability.

The outlet temperature is much more favorable (figure 16), with a range at the very middle of the required values.

Fig. 16. Variation of water temperature on the lateral water outlet.

Fig. 15. Distribution of temperature for bottom inlet of water.

(a) fluid temperature through front vertical section.

(b) fluid temperature through lateral vertical section.

(c) solid temperature through front vertical section.

Fig. 17. Distribution of temperature for lateral inlet of water.

(a) fluid temperature through front vertical section.

(b) fluid temperature through lateral vertical section.

(c) solid temperature through front vertical section.

Fig. 16. Variation of water temperature on the lateral water outlet.
Similar results have been obtained if water is introduced through bottom orifice (figure 17). The temperature of outlet water is somehow lower and the distribution is less favorable (figure 18).

![Graph showing variation of water temperature on the bottom water outlet.](image)

**Fig. 18.** Variation of water temperature on the bottom water outlet.

### 4 Conclusions

Numerical analysis of fluid flowing and heat transfer for an existing water heater revealed that temperature of electric heater is close to the maximum acceptable values of 900°C. The temperature of warm water is conforming to general requirements, but volumes of fluid with maximum temperature stagnate inside container. Simple constructive solutions, such as modification of position for heating element or reversing inlet and outlet orifices do not improve flowing and heat transfer. The new solution based on a helical heating element could be of significant benefit, since distribution of fluid temperature is more uniform and favorable. The most important improvement consists in more reduced loading of the heating element, which has a much lower maximum temperature, under 300°C, is more likely to improve durability.

**References:**


