Numerical simulation of induction heating thick-walled tubes

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Abstract. In the paper is shown the connection of two toolboxes in an Ansys Workbench solution for induction heating. In Ansys Workbench, Maxwell electromagnetism programs and Fluent have been linked. In Maxwell, a simulation of electromagnetic induction was performed, where data on the magnetic field distribution in the heated material was obtained and then transformed into the Fluent program in which the induction heating simulation was performed.

1 Induction heating

Induction heating is one of the heating variants, the principles of which are used mainly in industrial applications, melting, shaping, hardening, annealing of materials, but also in the home in the form of induction cookers and cooking plates.

Induction heating uses the principle of the action of the electromagnetic field described by Maxwell's equations on ferromagnetic material. The electrically conductive object is inserted into the alternating electromagnetic field of the induction coil during the induction heating through which the alternating current passes. As a result of electromagnetic induction, swirled currents are induced in the heated object, which have the opposite orientation as the current in the induction coil. Heating occurs due to resistive and hysteresis losses, the proportion of electrical and magnetic components depending on the electrical and magnetic properties of the heated material. The heat is generated directly inside the material, with the heated object and the inductor not in any mechanical contact.
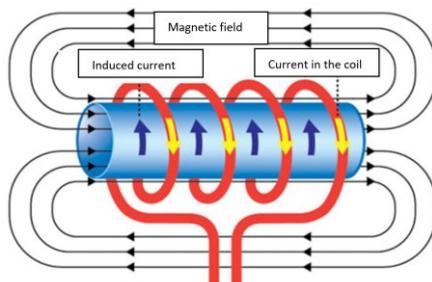
Fig. 1. Principle of the induction heating of the wall of the steel pipe [1].

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The principle of induction heating of a ferromagnetic steel pipe is also documented in Figure 1.

The source of electromagnetic radiation is each conductor through which the alternating current flows. In the case of induction heaters, the conductor is usually adjusted to a suitable shape with respect to the heated article in order to ensure sufficient efficiency of energy transfer from the emitter to the heated object and the required heating parameters (depth and range of the heated layer, temperature,...) [1].

Induction heating is therefore principally based on three basic physical phenomena:
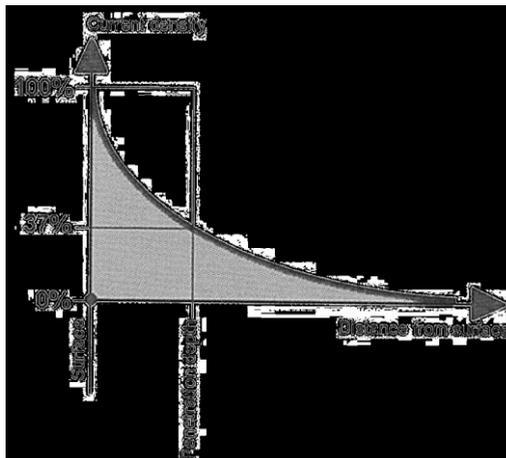- electro-magnetic induction,
- skin effects,
- heat transfer.

As a result of the skin effect, the current is ejected into the surface areas of the driver. The induced stream thus flows only with a small surface portion of the total cross-sectional area of the heated article. The current density from the surface of the conductor decreases exponentially. The distance from the surface of the wire along which the current density exponentially decreases to $1/e = 0.368$ the current density around the conductor, is referred to as the depth of penetration. In this layer, it is concentrated approximately 63 % induced current and 87 % heat generated. The depth of penetration depends on the electrical and magnetic properties of the material and also on the frequency of the current in the induction coil according equation: [2, 5]

$$\delta = \sqrt{\frac{\rho_{el}}{\pi \mu_0 \mu_r f}}, \qquad (1)$$

where, f – is the frequency of the current (Hz), ρ_{el} – specific electrical resistance (Ω.m), μ_r – relative permeability of the environment (-), μ_0 – is the vacuum permeability (H/m).

From equation (1) it shows that the depth of penetration, inter alia, depends on the frequency. Due to the fact that electrical resistance and especially permeability changes significantly with temperature, the penetration depth also depends on the temperature. At low temperatures, the conductive materials are strongly ferromagnetic, the penetration depth is small, resulting in a rapid heating of the surface of the body. However, after the Curie temperature is exceeded, the relative permeability drops to a value $\mu_r = 1$ and at the same time, the value of the specific electrical resistance increases, increasing the depth of penetration. The penetration depth also increases with increasing magnetic field strength.

**Fig. 2.** Dependence of the electrical current density on the distance from the surface [2].

By induction heating, materials of often very different electromagnetic properties are heated. For example, copper, aluminium, steel. Obtaining a temperature dependence of relative permeability on ferromagnetic materials is very complicated. In practice, it is necessary to base the measurements on the parameters [3].

In our case, the induction heating of the roughness tube of the diameter was simulated 918 mm (Figure 3). Where the required temperature after induction heating is on the tube surface 1 030 °C and on its inner part 1 000 °C with a tolerance ±20 °C.

2 Simulation of induction heating

One of the methods of optimizing induction heating is also the simulation of electro-thermal events in various applications. For this purpose, ANSYS Maxwell simulation program is used [4].

Since the tube wall heating is an axially symmetric problem, was in Maxwell 2D from a 3D predefined model (Figure 3) a simplified 2D model was created (Figure 4). This is an induction heating model with defined electrical parameters of the roughness tube with the geometric parameters of Figure 3.
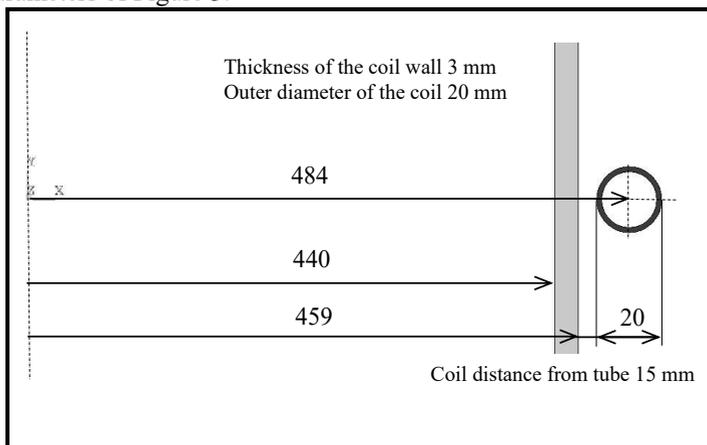
Fig. 3. Geometric parameters of inductor and tube.

In Maxwell 2D, the material requirements for each domain were defined as follows:
- for the surrounding area the selected material was Air,
- for a domain, presenting the tube is selected as Steel_1010,
- for a domain, presenting the coil, was selected the Cooper.
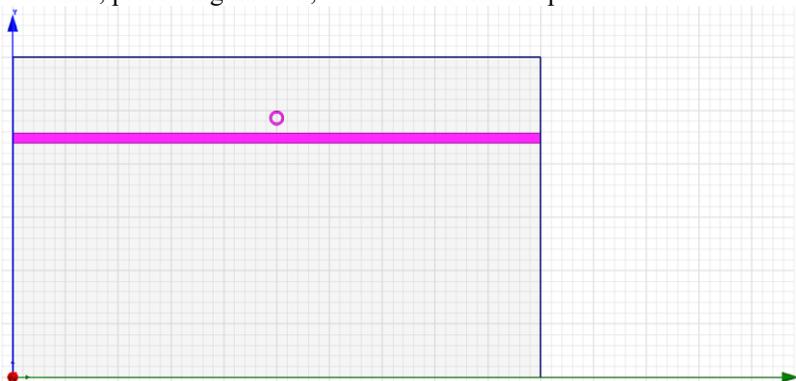
Fig. 4. Created 2D model in Maxwell 2D.

2.1 Model selection and boundary conditions

In Maxwell 2D, a Cartesian model, X, Y with Eddy Current was selected. The boundary condition of the Balloon for the boundaries of the surrounding space has been assigned and the matrix parameter assigned to the part of the model that represents the coil and will count the impedance. For the excitation, the magnitude of the current in the 9 kA coil was set.

The analysis setting allowed up to 15 calculations with 1 % error rate. In the solution, the frequency is set to 400 Hz and 0.0001 for nonlinear residues. Network creation has been left automated it was enough for these simulations.

2.2 Result from numerical simulation in Maxwell

The results thus obtained (Figure 5) from the numerical simulation were connected according to Figure 6 with Fluent Code Solution.
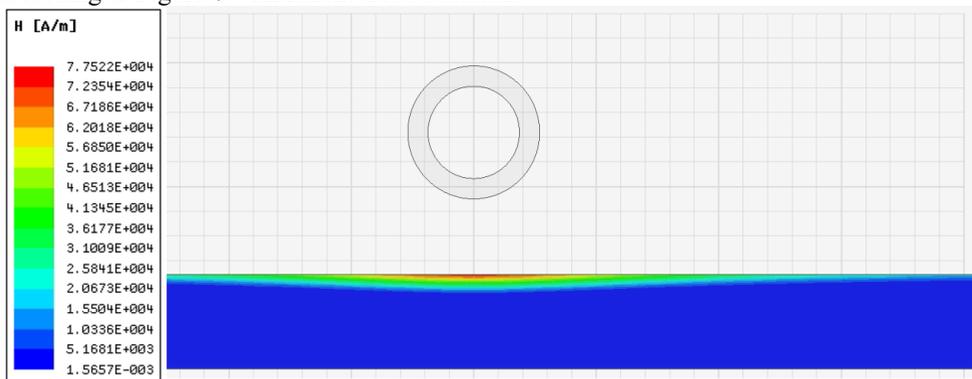

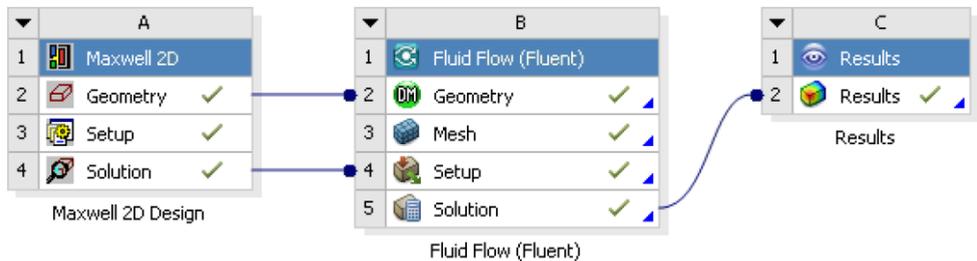**Fig. 5.** Result of the magnetic field intensity distribution in the tube wall.

Fig. 6. Connect Maxwell 2D and Fluent toolboxs.

3 Settings of the numerical simulation in a program Fluent

The created model in Maxwell 2D has been transformed into a model designer, where the model has been supplemented with the geometry that is needed for another solution, which is the subsequent cooling of the material after an induction heating. The position and space for cooling air, the position of the inductor and the cooling water position. Of course, the cooling water space did not need to be modeled because the surface to which the cooling water actually enters is along the cooling part and will be replaced by the dependence of the heat transfer coefficient on the wall temperature. After the model was modified, a computational mesh was created which had 313 199 2D cells (Figure 7).
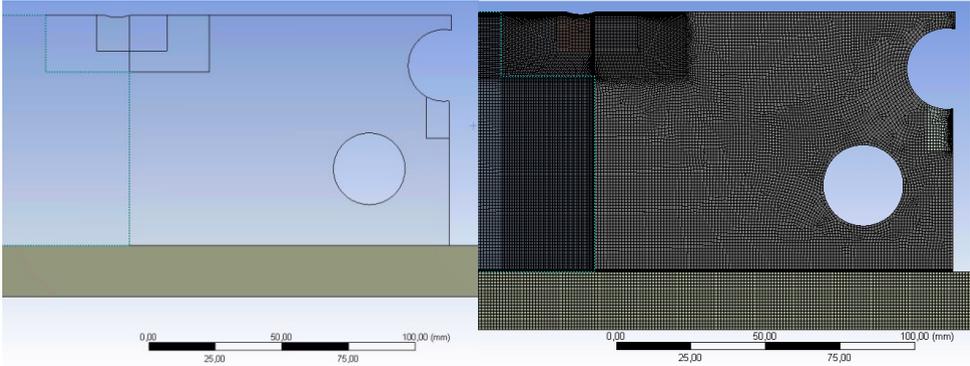
Fig. 7. 2D model after modification and created computational mesh.

After transferring the computing mesh in to Fluent was set up boundary conditions for the individual domains for induction heating Table 1.

Table 1. Boundary conditions for each domain.

Boundary conditions	Input parameter	Temperature	Radiation
Inlet_air	0 m/s	20 °C	
Wall_water	not entered	20 °C	1
Innet_wall	-	-	0.1
Walls	-	-	0.9

After the boundary conditions were set, it was necessary to assign the obtained electromagnetic field distribution from Maxwell to a particular domain using the function EM mapping – Volumetric Energy Source, which, after selecting a particular zone, has been assigned the desired electromagnetic field. The model thus prepared was launched as a time-dependent model first with energy and radiation only, which served to obtain the resulting temperature field distribution after the induction heating which could then begin to cool. The resulting field temperature distributions after the induction heating can be seen in Figure 8 and the temperature distribution in the tube wall (Figure 9).
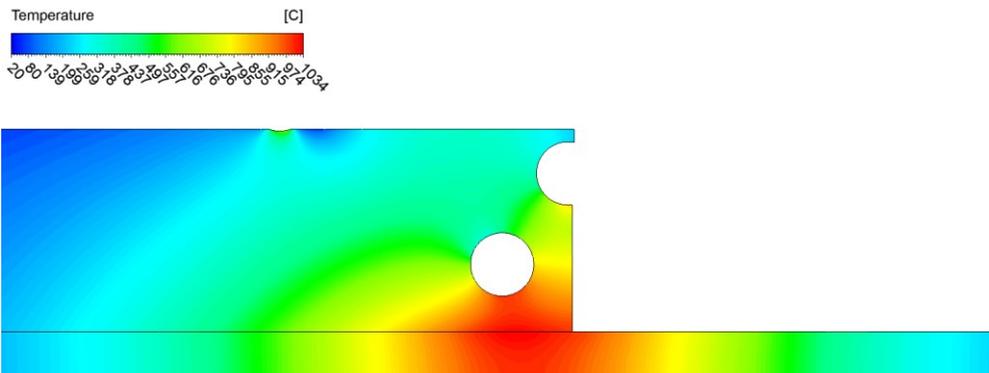
Fig. 8. Results of temperature field distribution after induction heating.
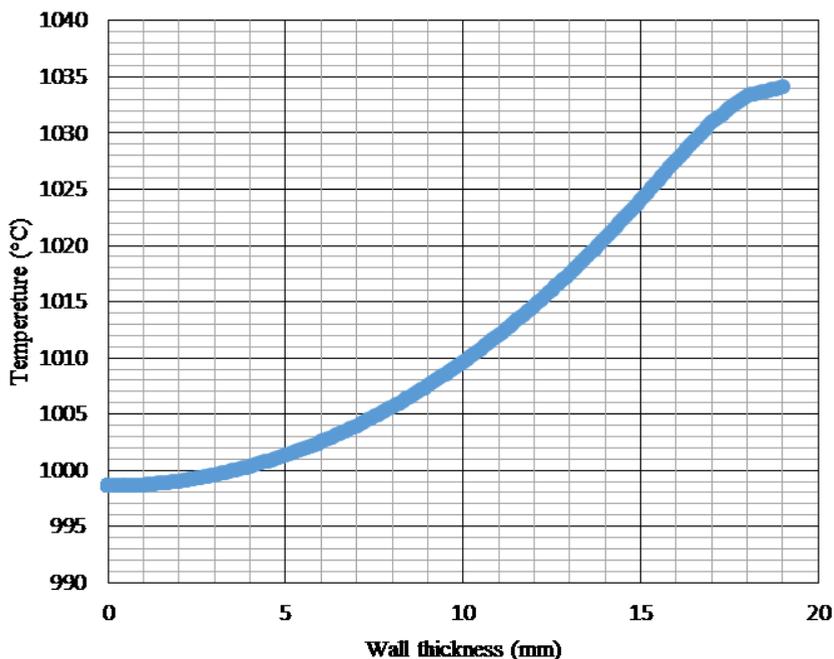
Fig. 9. Temperature distribution in the tube wall.

4 Conclusion

Numerical simulation of the temperature field change in the tube wall after induction heating, mild deformation and radiation showed that this physical, the technological process can be numerically modeled. This will further influence the process by, for example, cooling the surfaces of the oven after heating it by means of induction. It achieves further ways of reducing wall temperature after induction heating, which will ensure that the mechanical parameters of the pipe material are maintained even after the necessary technological induction heats.

References

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