Fully Non-linear Modelling of Induction Heating of Carbon Steel Using Open Source Simulation Tools

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Abstract

The paper describes simulation of induction heating process of ferromagnetic steel, when a full non-linear model is used: a temperature dependent B-H curve is taken into account. The full B(H,T) model is essential to obtain accurate results, which are confirmed by experimental validation. The paper also points out sensitivity of the model to slight variation of magnetic properties of material like Curie temperature, which might vary for steel of different grades. All results in the paper are obtained using open source simulation tools that demonstrates high accuracy compared to experimental results and benchmarked commercial software ANSYS Classic.

Introduction

Numerical simulation procedure is mentioned frequently as a major factor for the successful design of complex induction heating and hardening coils [1]. While manufacturing of physical prototypes cost significant price in terms of materials, machining expenses, labor costs, engineering and, finally, time, practice shows that simulation might be an efficient way to shorten a design workflow down to a single iteration if numerical methods are used wisely prior to physical prototyping. It also gave some additional advantage as the images and video of simulations can be used to demonstrate customers capability to design highly customized and highly efficient coils.

This paper aims to examine necessity to implement a full non-linear magnetic model for induction heating of ferromagnetic materials like carbon steel. Such model simultaneously includes a B-H curve and its quantitative change with temperature raise. If taken into account, a sophisticated B(H,T) model may increase accuracy of numerical prediction of heating process, thus, adding value to a simulation software. However, such non-linear modelling cannot be performed analytically or using simple calculation sheets, FEM software is necessary.

Regarding FEM software, traditionally, only enterprise level companies could afford numerical simulation tools, since not only high costs of software itself, but also long learning period and the highest qualification of engineers needed in order to run simulations in time-efficient way. This paper has the aim to demonstrate that such times will likely pass away very soon! Open source tools, which are not only free, but also provide access to their source code, nowadays, are able to perform very accurate and time-efficient calculations. Since full access to the source code is provided, such software are very cooperative to slightly changes of models, including such enhancement as B(H,T) non-linearity.

Nevertheless, beside accuracy, the biggest concern for open source simulation software is the significant time needed in order to set a case in an open source tools. Since they usually provide low quality user experience and, frequently, have no user interface at all, open source tools require up to thousand additional hours per year if compared with user-friendly commercial software.

Because of all mentioned factor, only enterprise level companies with significant R&D departments are able to run simulations in time-efficient way and, therefore, are able to produce efficient coils for heating and hardening of complex parts. However, since very recent time, CENOS platform developed the unique technology, which is able to connect the best of various open source tools and serve the SMB segment with the simulation platform, which is simple in use and focused on induction heating. Since the platform provides easy access to the open source algorithms, simulation is available for SMB, for the fraction of the price of enterprise software.

The present paper will demonstrate simulation cases of induction heating of a billet, which are performed using GetDP open source software, coupled with pre-processing tool Salome and post-processing tool ParaView, powered in time- and cost-efficient way by CENOS platform. The results of the simulation are compared with experimental works 1) by Scurtu & Turewicz at Leibniz University of Hanover [2] and 2) Di Luozzo et al. at University of Buenos Aires [3].

Mathematical model in general

Magnetic vector potential A and electric scalar potential V formulation is used (AV-formulation):

$$\nabla \times \left(\nu \nabla \times \vec{A}\right) - \nabla\left(\nu \nabla \vec{A}\right) + \sigma \left(\frac{\partial \vec{A}}{\partial t} + \nabla V\right) = 0, \;\; in\ \Omega_1;$$
$$\nabla \times \left(\nu \nabla \times \vec{A}\right) - \nabla\left(\nu \nabla \vec{A}\right) = J_s, \quad in\ \Omega_2;$$

$$-\nabla\left(\sigma\frac{\partial\vec{A}}{\partial t}+\sigma\nabla V\right)=0,\quad in\ \Omega_1.$$

Here, $\nu=1/\mu$ - reluctivity, μ - permeability, σ – electrical conductivity, J_s – source current density. Ω_1 stands for a electrically conducting eddy current domain (a workpiece to be heated), Ω_2 stands for a non-conducting domain (air) and a domain with a current source (a coil).

Magnetic vector potential at an outer surface of a computational domain is equal to 0:

$$\vec{A}=0.$$

For a symmetry axis of an axial symmetric model, the flux-parallel boundary condition is used:

$$\vec{n}\times\vec{A}=0.$$

For a symmetry plane, which is used to cut a half of the geometry in respect to the mirror-symmetry (in 2D representation, the plane is reduced to the line), the flux-normal condition is defined:

$$\vec{n}\cdot\vec{A}=0.$$

Temperature field is determined by solving the heat transfer equation:

$$\rho(\mathrm{T})c_p(T)\frac{\partial T}{\partial t}=\nabla(\lambda(T)\nabla T)+Q.$$

Here, ρ – density, c_p – specific heat capacity, λ – thermal conductivity, Q – Joule heat source. On the outer surface of the tube, both convective and radiation heat losses are set:

$$q=h(T-T_{amb})+\sigma_B\varepsilon(T^4-T_{amb}^4).$$

Here, σ_B – Stefan Boltzmann constant, h – heat transfer coefficient, ε – emissivity.

Magnetic field changes over the period of harmonic oscillations. Therefore, for the harmonic calculation, specific integration procedure should be introduced to describe non-linear magnetic properties in harmonic equation correctly. According to that, magnetic field intensity varies over the period in ferromagnetic material not as sinusoidal function, but linearization approach finds effective B_{eff} that leads to same integral energy as it would be in transient simulation [4]:

$$B_{eff}(H)=\frac{2}{H}\int_0^H B(H')dH'.$$

The mathematical model described in this section is solved numerically with the Finite Element Method (FEM), coded in open source tool GetDP. For time-efficiency, CENOS platform was used to set material and numerical parameters of the model in graphic mode as well as to combine GetDP computational algorithms with pre-processing tool Salome and post-processing tool ParaView.

Description of the validation cases

Validation of numerical models were performed using 3 different cases, each of the case stands for the respective experimental results (the references are provided):

Case 1.1 – linear model for aluminum, ref. [2];
Case 1.2 – μ(T) model for carbon steel, ref. [2];
Case 2.0 – B(H,T) model for carbon steel, ref. [3].

In the Case 2.0, the full non-linear magnetic model is represented by magnetic permeability as a function of both magnetic field intensity and temperature – μ(H,T):

$$\mu(H,T)=\frac{B(H)}{H}\left(1-\left(\frac{T}{T_C}\right)^{\alpha}\right)+\mu_0, \qquad (1)$$

where T_C is the Curie temperature, α is characteristic exponent of permeability temperature dependence and μ_0 is vacuum magnetic permeability. In the Case 2.0, $\alpha = 6$; the Curie temperature T_C=735 °C.

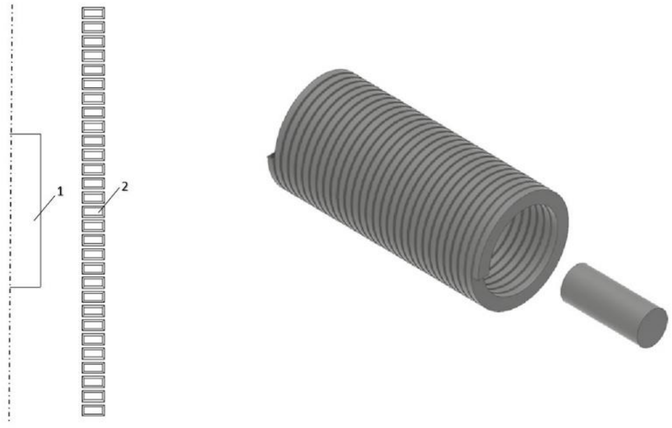

*Figure 1 – **Case 1.1 & 1.2**: 3D rendering of the parts (right) and the scheme of 2D axially symmetric system (left). On the scheme: 1 – the billet, 2 – the coil.*

*Figure 2 – **Case 2.0**: 3D rendering of the tube and the coil (right) and the scheme of 2D axially symmetric system (left). On the scheme: 1 – the tube, 2 – the coil.*

Table 1 – Case 1: Parameters of the validation cases

	Case 1.1	Case 1.2	Case 2.0
Geometric parameters			
Radius of the billet	30 mm		Inner: 16.5 mm/ Outer:
Length of the billet	150 mm		150 mm
Inner radius of the coil	70 mm		35 mm
Length of the coil	400 mm		50 mm
Number of windings	29		4
Operational parameters			
Current	1.3 kA	1.3 kA	725 A
Frequency	1.9 kHz	1.9 kHz	15 kHz
Material properties			
Material	aluminum	steel	
Thermal conductivity	λ(T), see Fig.3	λ(T), see Fig.4	
Heat capacity	c_p(T), see Fig.3	c_p(T), see Fig.4	
Density	2.45 g/cm^3	7870 g/cm^3	
Electric conductivity	σ(T), see Fig.3	σ(T), see Fig.4	
Magnetic properties			
Over temperature	**constant μ = 1**	**μ(T)**, see Fig.5	**B(H,T)**, see Eq.(1)
B-H curve	-	-	**B(H,T)**, see Fig.6

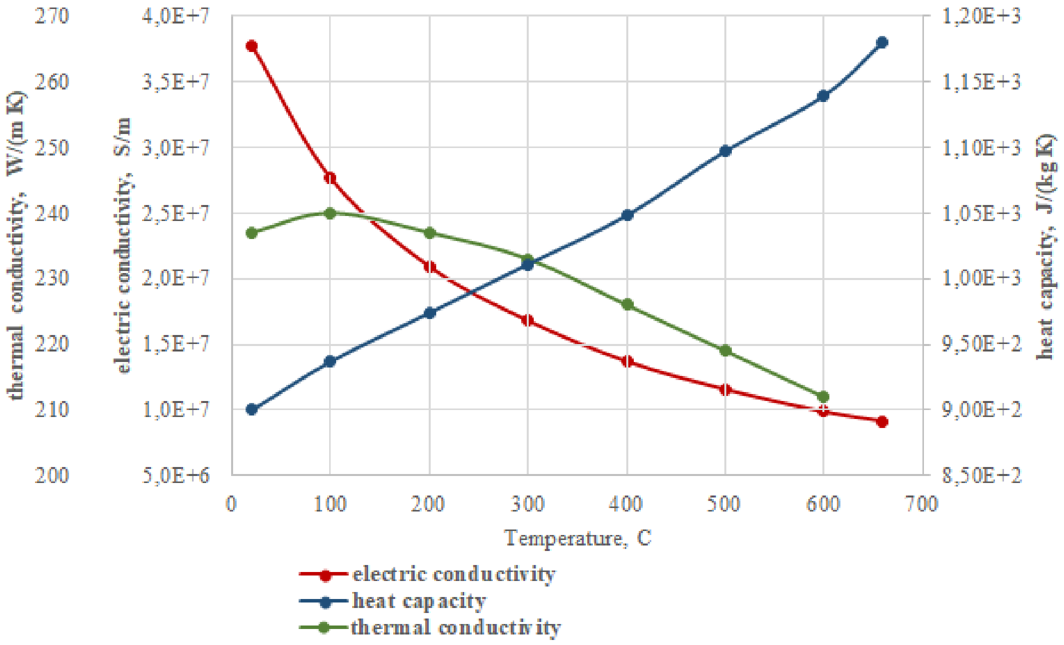

*Figure 3 – **Case 1.1**: temperature dependent material properties of **aluminum**.*

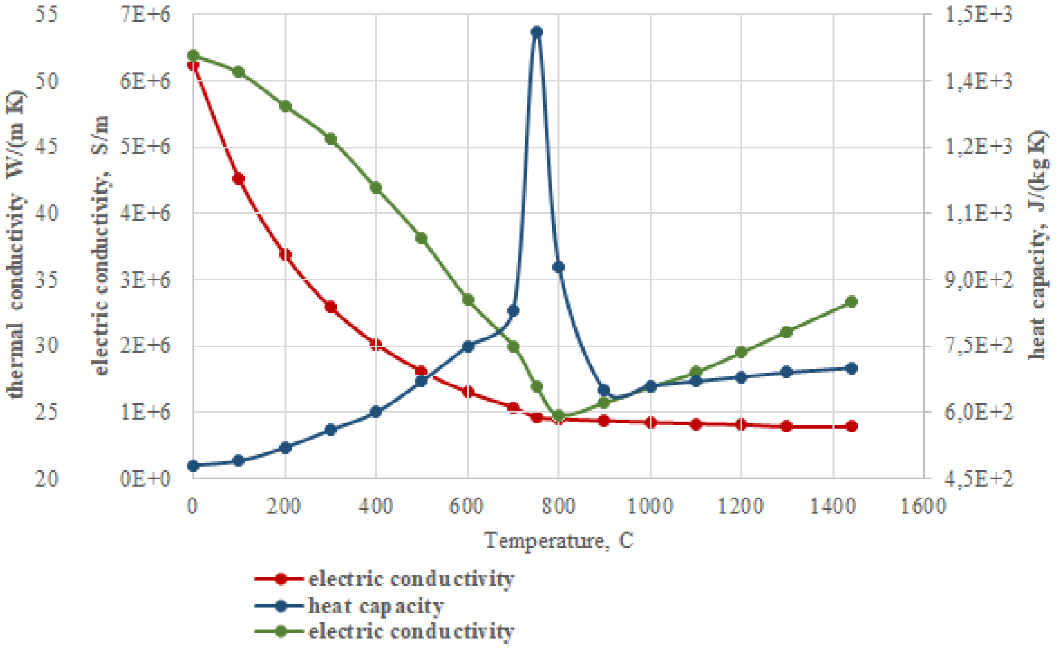

*Figure 4 – **Case 1.2 & 2.0**: temperature dependent material properties of **steel**.*

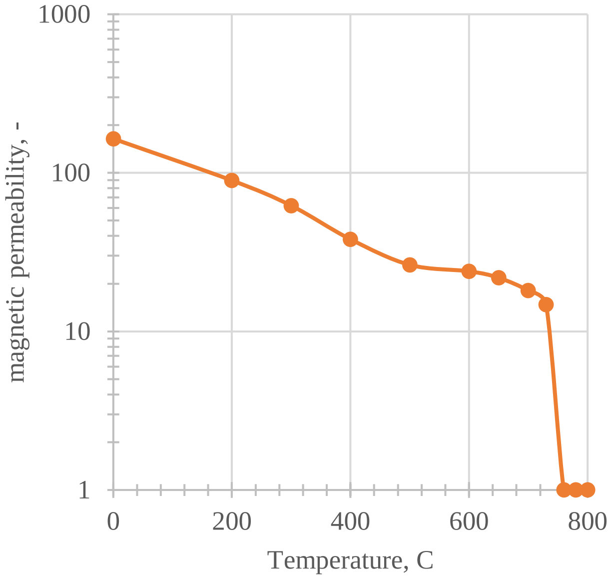

*Figure 5 – Case 1.2: Magnetic permeability of steel μ **over temperature.***

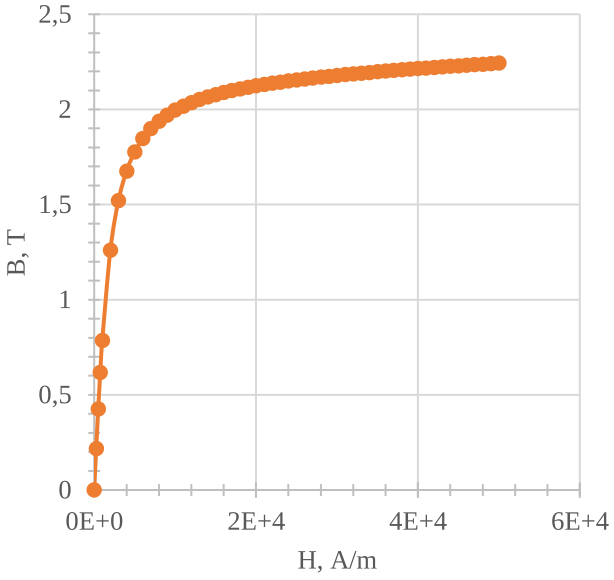

*Figure 6 – Case 2.0: **B-H curve***

Case 1.1: Linear model for aluminum

Case 1.1 represents the simple linear model for induction heating of the aluminum billet. Fig.7 demonstrates that the results, obtained using the open source software GetDP, perfectly match both results of benchmark simulation by ANSYS and the experimental results [2]. The results represents temperature in the middle of the billet, at the symmetry axis, over heating time.

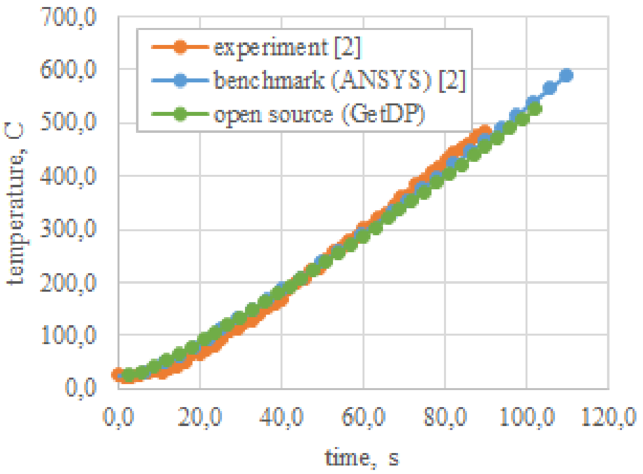

*Figure 7 – **Case 1.1**: Temperature at the middle of the aluminum billet over heating time. Experimental results and benchmark calculation ref. [2].*

Case 1.2: μ(T) model for steel

It is transparent, that induction heating simulation of steel requires to consider non-linear properties of ferromagnetic materials. Frequently, simulation is limited to temperature dependence of magnetic properties μ(T) and does not take into account a B-H curve. Such approach is demonstrated also in the article [2], which presents the experimental results of induction heating of a steel billet obtained by Scurtu & Turewicz at Leibniz University of Hanover. Beside the experimental results, the authors published numerical results by ANSYS Classic, which is well-known accurate benchmark software (see Fig.8). While the simulation by Scurtu & Turewicz is performed taking into account only temperature-dependence of magnetic permeability μ(T), the simulated temperature perfectly matched the asymptotic (steady state) value, however, significantly underestimates temperature during transient heating. E.g., at 10th second, the benchmark model of ANSYS predicts the surface temperature of the steel billet 100 °C less than measured during the experiment.

The simulation by open source tool GetDP coincides with the benchmark simulation, even more, slightly better predicts transient temperature during heating (see Fig. 8). The last fact is just because of adaptive time step, which allowed more accurately resolve the temperature raise. Nevertheless, the figure clearly demonstrates inability of the simple μ(T) model to predict temperature at the surface of the steel billet during the heating process.

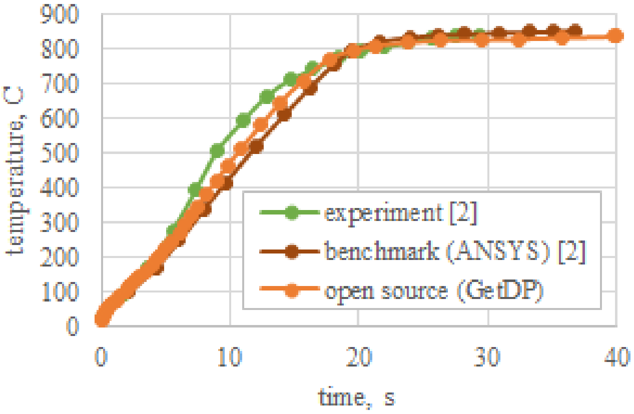

*Figure 8 – **Case 1.2**: Temperature at the surface of the steel billet over heating time. Experimental results and benchmark calculation of **μ(T) model** ref. [2].*

Does a B-H curve help to predict the temperature raise accurately? While there is no exact information available neither regarding the grade of the steel used in the experiment, nor B-H properties of it, the simple calibration of some analytical B-H model demonstrates improvement of simulation result on Fig. 9. However, one can recognize slightly overestimated temperature after 10th second of heating. Since B-H curve here is just calibrated and does not ground in material properties of the steel, we decided to double check necessity of the B(H,T) model in the Case 2.0, which provides very accurate experimental data.

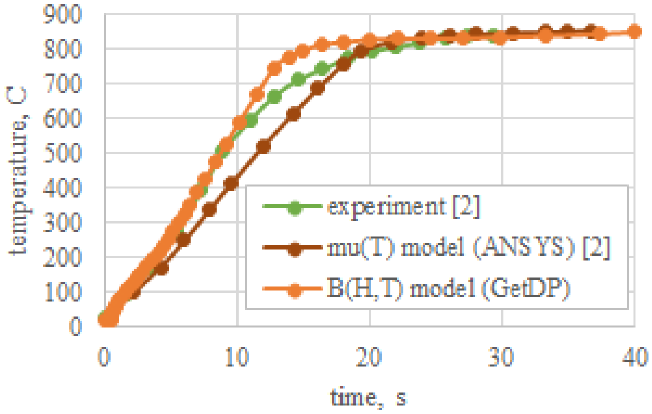

*Figure 9 – **Case 1.2**: Temperature at the surface of the steel billet over heating time. Calibrated **B(H,T) model** and μ(T) model (ref. [2]) benchmarked to experimental results [2].*

Case 2.0: B(H,T) model validation

The Case 2.0 demonstrates accurate validation of B(H,T) model in respect to experimental data obtained by Di Luozzo et al. at the University of Buenos Aires [3]. The non-linear model is represented by Eq.(1) and Fig.6. Fig.10 demonstrates numerical mesh created for the following simulation.

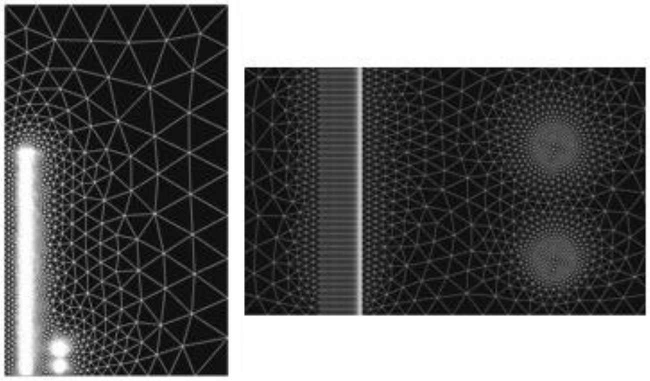

Figure 10 – Case 2.0: Model mesh

While Fig.11 demonstrates simulated temperature distribution at the surface of the billet, Fig.12 presents the essential results, comparing temperature over time at the surface of the billet. Temperature maxima is located in the coil region and it falls rapidly outside of coil where no heating source is present. The curves represent the points at different distance from the plane or mirror-symmetry of the system.

Fig.12 demonstrates good match of simulation results with the accurate experiment.

Discussion of the results

In general, good agreement between numerical and experimental results is achieved. Main discrepancies are as follows:

- change in heating rate at the symmetry plane appears 2 seconds earlier in numerical results rather than according to the experimental data. It might be because of the fact, constant voltage regime was carried out at the experiment, while only constant current regime in possible to simulate in 2D approximation. So, while the current in the simulation model was constant during all simulation time, it was, obviously, increasing during the initial short time moment in the experiment;
- change in the heating rate at the symmetry plane appears at lower temperatures ($\Delta T \approx 15$ K) in simulation results than in experimental results. We would like to argue here that the precise Curie point for the steel used is not known. Simulations at different Curie temperatures show that this change always appears slightly above (10-15 K) Curie point (see Fig.13 and further discussion).

Change in heating rate appear at 747 °C, which is 10 degrees higher than Curie point. The same character is observed in simulations for variation of Curie temperature (see Fig.13). Furthermore, increased heating rate appears immediately after Curie point for short period. This might be explained with electromagnetic effect of joined materials [5], which leads to local Joule heat maxima in non-magnetic part of steel above Curie point.

Fig. 13 demonstrates sensitivity of the B(H,T) model to Curie temperature. While for many steel grades is not known, variation of T_C might lead to slightly different results in heating simulation.

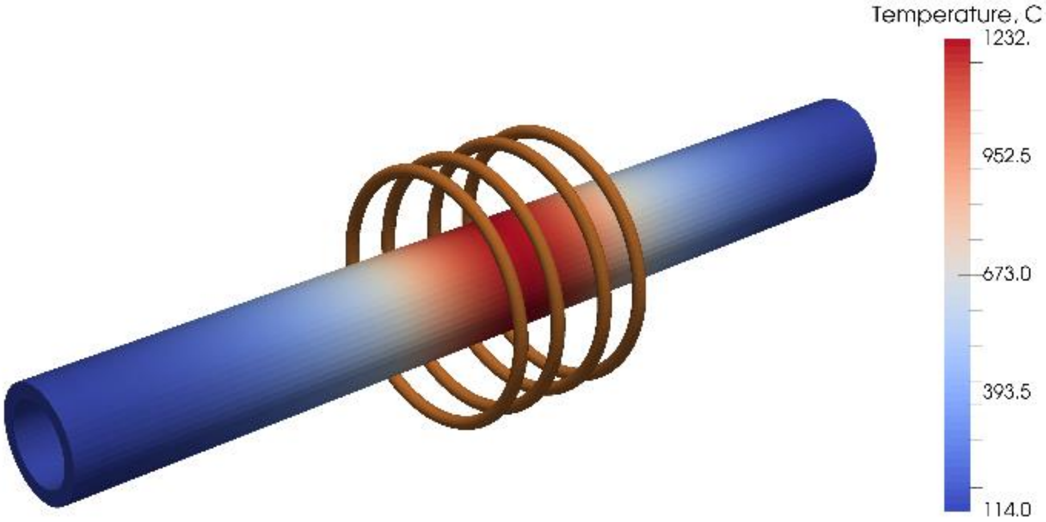

Figure 11 - Case 2.0: Temperature distribution in the tube after 120 seconds

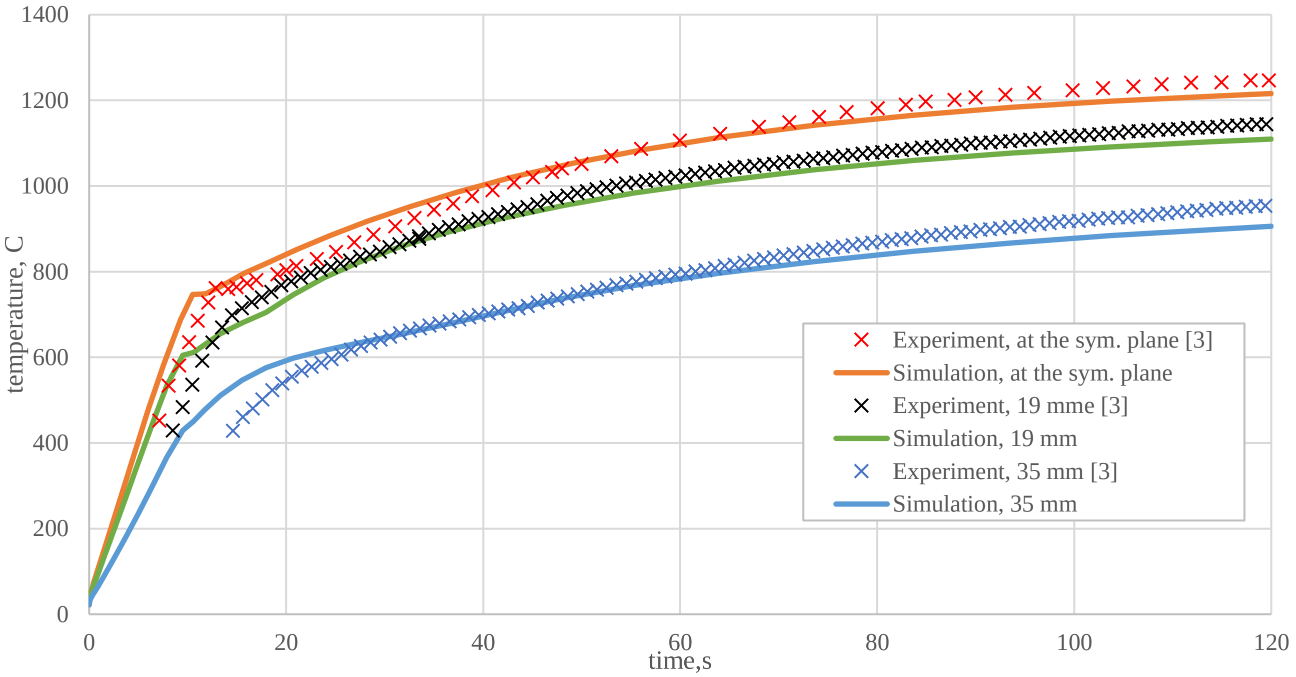

*Figure 12 – **Case 2.0**: Simulation and experimental results (ref. [3]) of temperature at the surface of the steel billet. The curves differs with the point where the temperature was measured, the distance from the symmetry plane is specified in the legend.*

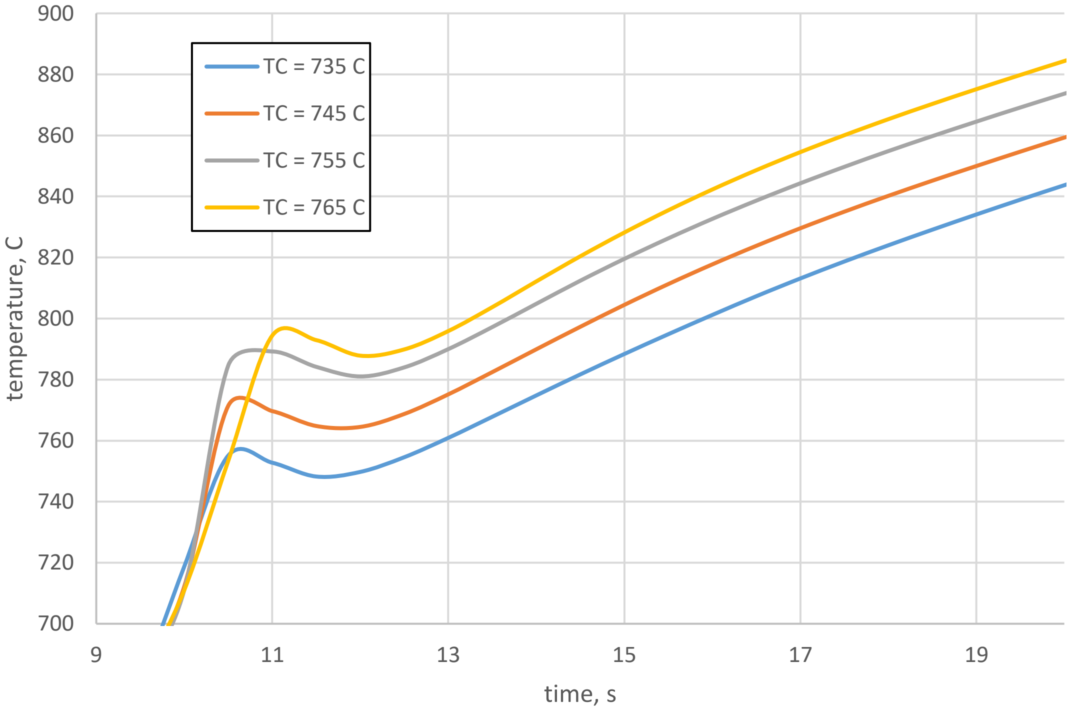

*Figure 13 – **Case 2.0**: Variation of Curie temperature in the B(H,T) model (Eq.1).*

Conclusion

Open source software GetDP has proven to be very reliable for modeling induction heating applications, especially due to its capability to capture temperature dependent material properties and non-linear magnetic effects. Results obtained with GetDP are in good agreement both with ANSYS commercial software and experimental results.

Simulation of non-magnetic materials or the materials with linear magnetic properties is easy to perform with the highest level of accuracy, since mathematic model is relatively simple. The results shown in the paper demonstrated perfect match with the experimental results.

Nevertheless, simulation of such ferromagnetic materials as steel request more accurate description of non-linear magnetic properties. Although, temperature dependent magnetic permeability μ(T) leads to satisfactory prediction of asymptotic (steady state) temperature, it might significantly underestimate temperature at the surface of soft magnetic materials like steel while heating. Then, the full non-linear model, which includes B(H,T), leads to accurate prediction of temperature, which was validated by experimental results.

We would like to point out that turning from the linear model to the full non-linear model for ferromagnetic materials, results of simulations become very sensitive to material property data. While in many practical cases, there might be insufficient knowledge of exact material properties, it might be reason for non-accurate prediction of heating pattern. As the example, slightly variation of the Curie point, which depends on steel grade, was simulated in the paper, which led to variation in heating pattern of the billet.

At the end, we would like to point out the value of CENOS platform, which enabled for the authors of the paper time-efficient simulation of induction heating problems using open source algorithms of GetDP software. CENOS turned out into the simple, fast and accurate way to perform heating simulation.

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Acknowledgement

L. Scurtu and N. Di Luozzo are gratefully acknowledged for providing detailed data of their experiments (referenced in the paper) and some clarifying discussions.