

Modeling of Induction Heating with Moving Load for Thermal Homogeneity Optimization

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Abstract

Induction heating of moving metallic charges is widely used in industrial processes requiring precise control of thermal exchanges. A core issue is to ensure both thermal homogeneity and sufficient exposure of all material points to temperatures above the melting threshold during the down motion of the moving charge. This work presents the development of a numerical model using Comsol Multiphysics®, designed to predict the temperature field in a moving load subjected to induction heating and correlated with experimental data. The model couples electromagnetic and heat transfer physics. Induced currents are computed from the electromagnetic field and used as volumetric heat source for thermal model, enabling also the treatment of phase change. The significant motion of the load through the inductor is considered through a moving and sliding mesh approach. A dedicated post-processing method is implemented to evaluate the time spent above the melting temperature, providing a relevant metric to assess process performance. The modeling approach is first validated against experimental measurements, demonstrating good agreement in terms of temperature evolution and spatial distribution. Once validated, the model is used to perform parametric studies aimed at optimizing operating conditions. In this context, the influence of input power and charge velocity is studied to meet process objectives. The results highlight the interplay between power and velocity in controlling both thermal gradients and exposure time. The proposed approach enables the identification of optimized operating conditions that ensure all points within the charge reach and maintain temperatures above the melting threshold while preserving acceptable thermal homogeneity. This work provides a predictive framework for process optimization in induction heating applications involving moving loads.

Keywords: Induction Heating, Electromagnetism, Surface-to-surface Radiation, Moving Mesh

Introduction

Induction heating has become one of the most efficient technologies for rapidly heating electrically conductive materials in numerous industrial sectors, including heat treatment, forging, brazing, additive manufacturing, rolling, and continuous production lines. The technology offers several advantages over conventional heating methods, including high energy efficiency, localized heating, rapid thermal response, and excellent process controllability. In many industrial applications, the workpiece continuously moves through one or several induction coils. The interaction between the alternating magnetic field generated by the inductor and the moving metallic part induces eddy currents whose dissipation produces the required heating. The resulting temperature distribution depends on numerous coupled parameters such as generator power, excitation frequency, coil geometry, workpiece velocity, material properties, and thermal boundary conditions. Because of these numerous interacting phenomena, numerical simulation has become an indispensable engineering tool for process optimization. Modern finite-element

software such as COMSOL Multiphysics® allows the simultaneous solution of electromagnetic and thermal physics while offering advanced capabilities for moving geometries and nonlinear materials [1].

Although induction heating has been widely studied, simulating continuous heating of moving workpieces remains considerably more challenging than stationary configurations [2], due to several nonlinear phenomena that must be addressed simultaneously. First, the relative motion between the workpiece and the stationary coil continuously alters the distribution of induced currents and Joule losses. Second, and more critically, the temperature-dependent electrical conductivity of the metal and crucible material makes the electromagnetic solution itself temperature-dependent, requiring the electromagnetic problem to be solved repeatedly throughout the transient simulation rather than only once as in classical sequential approaches. Finally, at elevated temperatures, radiative heat transfer becomes a dominant cooling mechanism, and simplified models considering only ambient radiation tend to underestimate losses by neglecting surface-to-surface exchanges between the workpiece, the coil, and nearby components.

The present work aims to develop a fully coupled multi-physics model accounting for all these phenomena within a single transient simulation, with particular attention to its numerical implementation in COMSOL Multiphysics®, including moving geometries, nonlinear electromagnetic properties, prescribed electrical power, and surface-to-surface radiative heat transfer

Geometry, Material and Model Description

The industrial system considered in this study consists of a stationary multi-turn induction coil through which a metallic workpiece moves at variable speed. It is illustrated in Figure 1. For confidentiality reasons, only a simplified geometry is presented, which does not correspond to the complex industrial configuration but retains its essential geometrical features relevant to the induction heating process. For the same confidentiality reasons, all quantities presented in the following figures — including power, magnetic flux density, temperature, and time — are given in non-dimensional (normalized) form (for example, time is expressed in dimensionless form as t/τ , where τ is used as a reference time). The induction coil is composed of several concentric turns connected to a power supply generator. The moving charge follows a straight trajectory passing through the central region of the inductor where the magnetic field intensity is maximal. Its velocity can vary over time. Because the electromagnetic field extends beyond the immediate vicinity of the coil, the computational domain also includes an air region sufficiently large to minimize boundary effects. Infinite element domains are employed to reproduce the open magnetic environment while maintaining a reasonable computational cost.

The workpiece motion is represented using the “Moving Mesh” functionality available in COMSOL Multiphysics®. A 2D-axisymmetric approach is used for this work.

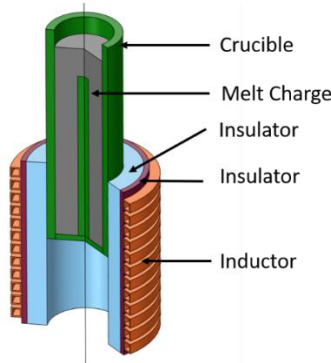


Figure 1. Problem geometry

The materials used in the model are as follows: the inductor is made of copper; the crucible is made of graphite, providing both electrical conductivity for efficient inductive coupling and high thermal resistance; the charge is metallic; and several non-conductive materials are used for the surrounding screens.

Modeling and Governing Equations

Each “physics” solved in COMSOL Multiphysics® is detailed with the different assumptions used in this work.

Electromagnetism

The Magnetic Fields interface is used to compute electromagnetic fields by solving the following Maxwell’s equations:

$$\nabla \times \frac{1}{\mu_0 \mu_R} \nabla \times \mathbf{A} + (j\omega\sigma - \omega^2 \epsilon_0 \epsilon_R) \mathbf{A} = \mathbf{0}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{E} = -j\omega \mathbf{A}$$

where $\mathbf{A}$ is the magnetic vector potential, $\mathbf{B}$ the magnetic flux density vector, $\mathbf{E}$ the electric field vector, μ the magnetic permeability, ϵ the electric permittivity, σ the electrical conductivity of the medium (that can vary with the temperature) and ω the angular frequency.

As the electrical power is known at the generator and the electrical circuit is not detailed in this paper, a numerical power supply is adopted to supply the inductor through the “Coil Domain” formulation:

$$P_{coil}(t) = \frac{1}{2} \text{Re}\{V_{coil}, I_{coil}^*\}$$

where V_{coil} is the induced voltage calculated by integrating the electric field along the coil and I_{coil}^* , the conjugate intensity in the coil.

Heat Transfer and Surface-to-Surface Radiation

Due to the high current flowing through the metallic components, thermal energy is generated. The following energy equation is solved in the metal pieces:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot [-k \nabla T] = Q$$

where T is the temperature, $\mathbf{u}$ the charge velocity, ρ the density, k the thermal conductivity and C_p the heat capacity of the different materials, and the volumetric Joule heating source is given by:

$$Q = \frac{\sigma}{2} |\mathbf{E}|^2$$

The “Phase Change Material” interface is also used to describe the possible phase change of the charge during the process and to consider the latent heat in the thermal balance. Concerning the boundary conditions, the inductor is assumed to be sufficiently cooled such that a Dirichlet boundary condition, equal to the cooling water temperature, is imposed at the internal walls of the coil turns ($T = T_{water}$). Natural convection and ambient radiation are taken into account on the exterior boundaries with:

$$-\mathbf{n} \cdot (-k\nabla T) = \varepsilon\sigma(T_{amb}^4 - T^4) + h(T_{amb} - T)$$

with ε the emissivity of the surface, σ the Boltzmann constant, h a heat transfer coefficient T_{amb} the ambient temperature.

Radiative heat transfer becomes increasingly significant as the workpiece temperature rises and can represent a substantial fraction of the total heat losses (quantified further in the Results Section). In this work, the “Surface-to-Surface Radiation” interface is used, which computes radiative exchange factors between all participating surfaces and solves the corresponding nonlinear radiation balance. As the relative position between radiating surfaces continuously changes with the workpiece motion, view factors are automatically updated throughout the transient simulation. A dedicated sensitivity study was performed to determine an appropriate update frequency, comparing several intervals in terms of maximum temperature, thermal profile along the workpiece, and overall energy balance; the selected frequency was validated by confirming that further increases produced negligible changes in the results while limiting computational cost.

Numerical methods

A “Frequency-transient” study is used to solve the “Magnetic Fields” equations at a fixed frequency, while the “Heat Transfer in Solids” equations are solved in a transient manner. The continuous displacement of the workpiece through the induction coil requires a dedicated numerical strategy to account for the relative motion between the electromagnetic source and the heated component. In this study, a sliding mesh approach was implemented to represent the movement of the workpiece while preserving the quality of the finite-element discretization. The computational domain is divided into two main parts: a stationary region containing the induction coil and surrounding air (on the right of the vertical magenta line in Figure 2), and a moving region containing the workpiece and its associated mesh (on the left of the vertical magenta

line in Figure 2). The interface between these two domains is defined as a sliding boundary allowing the moving mesh region to translate through the stationary domain without modifying the local element topology. This approach offers several advantages for long-distance translations. Since the mesh associated with the workpiece undergoes a rigid-body displacement rather than a continuous deformation, element distortion is avoided even for large travel distances. As a result, the electromagnetic and thermal fields can be computed on a high-quality mesh throughout the complete heating process without requiring repeated remeshing operations. The sliding interface ensures continuity of the relevant physical quantities between the moving and stationary domains. A weak-constraint formulation is employed to ensure a precise description.

A mesh sensitivity study was performed to ensure that the sliding interface did not introduce significant numerical diffusion or interpolation errors. The mesh density in the vicinity of the induction coil and the workpiece surface was refined to accurately capture the skin effect and the strong gradients of electromagnetic losses by using boundary layers (see Figure 3).

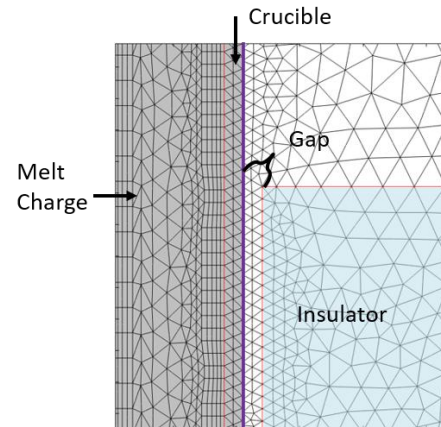


Figure 2. Sliding mesh between the crucible and the gap separating the crucible from the insulator allowing relative movement

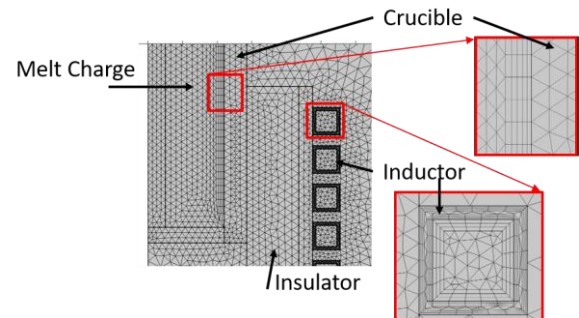


Figure 3. Boundary layer mesh with zoomed view in the melt charge (top right) in an inductor turn (bottom right)

Simulation results and discussion

The numerical model described in the previous section was used to simulate the induction heating process of a moving charge and to investigate the influence of the main operating parameters (charge velocity and inductor power) on its thermal history. Figure 4 presents the temporal evolution of the power distribution induced within the charge (in blue) as it travels through the inductor. For a better understanding, the Figure 5 illustrating the charge position at four different instants can also be consulted.

At the beginning of the simulation ($t/\tau = 0$), the charge has not yet entered the active zone of the inductor, which explains why copper losses (in red, Figure 4) dominate, accounting for approximately 63% of the total active power, while the charge and the crucible (blue and green respectively in Figure 4) only receive a comparatively smaller share, around 23% and 14%, respectively. As the charge progressively enters the inductor and advances into the region of strongest electromagnetic coupling, the share of power dissipated in the charge and crucible increases accordingly, reaching maximum values of approximately 37% and 24% around $t/\tau \approx 15 - 20$, while copper losses correspondingly decrease to a minimum of about 38%. Beyond this point, as the charge starts exiting the active zone, the trend reverses: copper losses increase again, reaching about 51% by the end of the simulation. It should be noted that, at the end ($t/\tau \approx 33$), the charge has only exited the active zone by about 50%, which mainly explains why the final copper losses remain lower than the initial value of 63% recorded when the charge had just entered the inductor. This asymmetry between the initial and final states further illustrates how the relative position of the charge with respect to the inductor directly governs the efficiency of the power transfer: the closer the charge is to the region of optimal electromagnetic coupling, the smaller the share of power dissipated as copper losses rather than usefully transferred to the charge itself. Finally, the consistent agreement between the total active power (in cyan in Figure 4) and the sum of the three individual contributions (in magenta dots in Figure 4) throughout the simulation further validates the accuracy of the power balance computed by the numerical model.

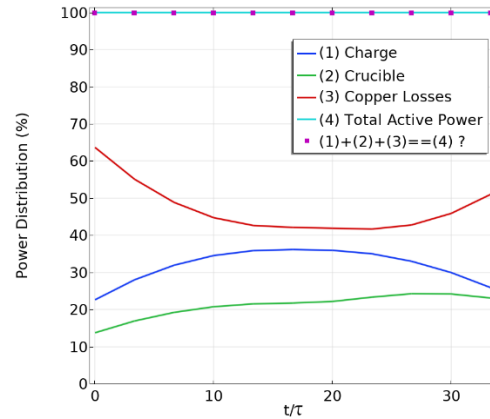


Figure 4. Power Distribution

The magnitude of the magnetic flux density together with the resulting Lorentz forces computed for several positions of the charge within the inductor are shown in Figure 5. Both quantities vary significantly as the load advances, with maxima occurring when the charge is aligned with regions of highest coil density. Electromagnetic stirring is characterized in terms of its intensity, through the computation of the Lorentz forces induced within the molten charge (Figure 5). However, this stirring effect is not accounted for in the thermal model, as the resulting fluid flow within the liquid charge is not resolved.

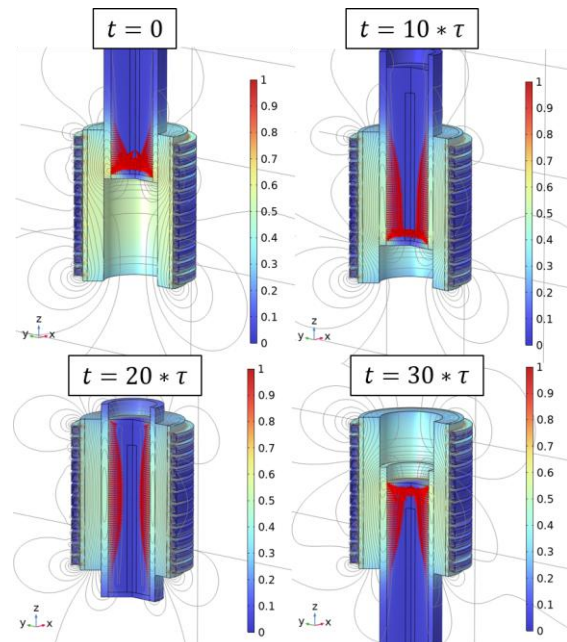


Figure 5. Magnetic Flux Density norm (color field) and Lorentz Forces (red arrows) at different positions

The thermal consequences of this electromagnetic behavior are illustrated in Figure 6 and Figure 7, which compare the temperature fields obtained without and with surface-to-surface radiation, respectively. In Figure 6, only radiative losses to the

ambient environment are considered, meaning that heat exchange between facing surfaces of the charge is neglected. This leads to an underestimation of the temperature in regions where the local geometry, such as mutually facing surfaces, would otherwise promote additional radiative heating. When surface-to-surface radiation is included (Figure 7), the resulting temperatures are noticeably higher in these regions by 30%, confirming that this mechanism is not negligible and must be accounted for to obtain a physically realistic prediction.

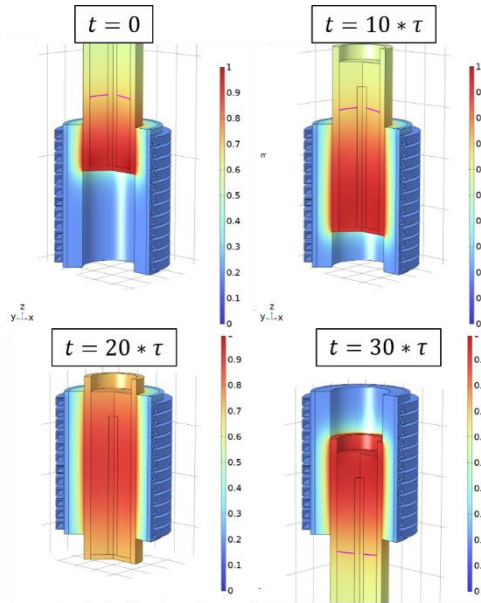


Figure 6. Temperature Field at different positions with surface to ambient radiation, with melting temperature isotherm in magenta

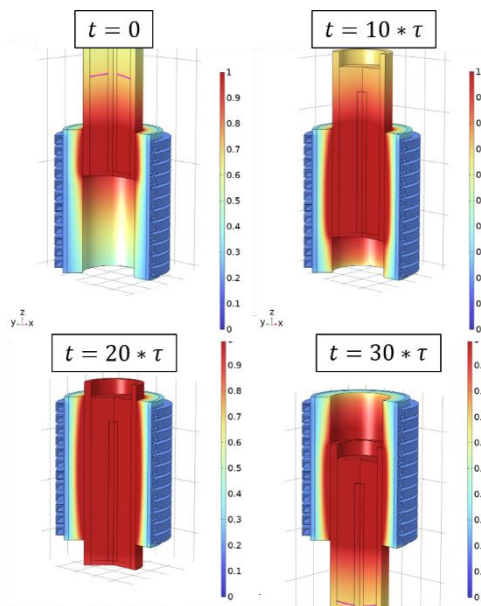


Figure 7. Temperature fields at different positions with surface-to-surface radiation, with melting temperature isotherm in magenta

Finally, Figure 8 presents, for each point of the charge, the cumulative time spent above the melting temperature. It is computed using the following time integral, implemented via an extra Ordinary Differential Equation (ODE). This quantity could also be computed using the “Time Integral Dataset” available in the Results Section:

$$\delta\tau = \int (T > T_{fusion}) dt$$

This map provides a synthetic and practical indicator of both thermal homogeneity and process efficiency: regions with very short durations correspond to locations that never reach, or only briefly exceed, the melting point, while excessively long durations may indicate local overheating or unnecessary energy input. From a process design standpoint, an ideal configuration would minimize the spread of this duration across the charge volume - ensuring that all points reach the melting temperature within a similarly short time window - rather than simply maximizing the average temperature.

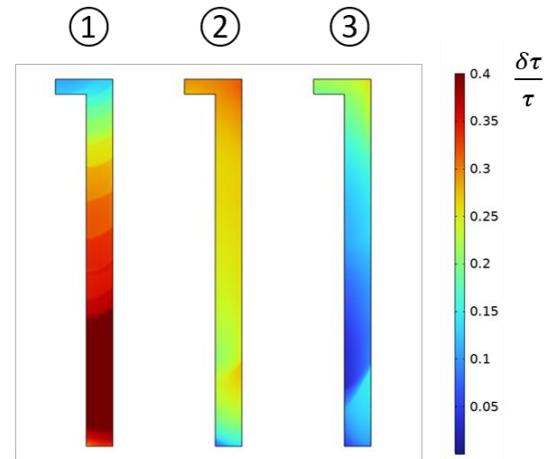


Figure 8. Time spent above the melting temperature for different configurations

Figure 8 shows results for three charge velocities, denoted ①, ② and ③, from slowest to fastest. As expected, increasing the charge velocity globally reduces the time spent above the melting temperature: the reference case ① exhibits the longest exposure durations, while ② and ③ show progressively shorter durations as the velocity increases. This trend directly reflects the reduced residence time of each point of the charge within the high-power region of the inductor as the velocity increases. In addition to the duration above the melting temperature, another relevant indicator to consider is the maximum temperature reached at each point of the charge. Indeed, an excessively high temperature, even if reached only locally or transiently, may be detrimental to the process leading to the degradation of the charge properties.

This indicator is therefore complementary to the exposure duration discussed above: while the latter ensures that melting is achieved throughout the charge, the maximum temperature criterion ensures that the process does not induce excessive overheating in any region. Both indicators were therefore considered jointly to define an optimal combination of charge velocity and inductor power, ensuring complete and homogeneous melting while avoiding excessive peak temperatures.

Overall, these results show that the proposed model captures the essential coupled electromagnetic-thermal phenomena governing induction heating of a moving charge and can be used as a predictive tool to define relevant process indicators. In particular, charge velocity and inductor power emerge as the two parameters most directly controlling the trade-off between thermal homogeneity, melting time, and complete melting: higher power reduces melting time but may increase local heterogeneities if velocity is not adjusted accordingly, while lower velocity improves coupling at the cost of longer processing times. The model thus provides a practical basis for identifying optimal operating windows balancing energy efficiency, process duration, and thermal uniformity.

Conclusions

This work presents a fully coupled electromagnetic-thermal model for induction heating of a moving charge, accounting for nonlinear material properties, moving geometries, and surface-to-surface radiation. The model successfully identifies key process indicators (thermal homogeneity, melting time, maximum temperature) and demonstrates that charge velocity and inductor power are the primary control parameters for optimizing the process.

Future work will focus on extending the model to fully coupled magnetohydrodynamic simulations to capture the effect of electromagnetic stirring on thermal homogenization, thereby improving the prediction of the temperature field within the charge. The model will also be validated against experimental measurements at the inductor level to assess the circuit-coupled approach, while thermocouple measurements will be used to compare the predicted and measured thermal fields.

References

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