A User-Friendly COMSOL Multiphysics Application to Design a Generic Induction Furnace

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Abstract

Metallurgical process of metal melting requires tremendous amounts of energy. A modern way to optimise the power required is to use an induction furnace. Such furnaces are efficient but more challenging to design and to run than a conventional device.

Figure 1 – Metal casting after melting process - Photo by Ludomił Sawicki on Unsplash

In order to design an induction furnace and to optimize the charge melting, a COMSOL Multiphysics® application is developed. This application runs a furnace electromagnetic model.

The inductor, supplied with an alternative electrical current, creates a variable induction field $\vec{B}$. Due to this field, an induced current appears in the melt and in the crucible. Thus, the charge starts to heat up.

The input current frequency, the inductor properties and the melt material have a huge impact both on the heat quality and the meshing refinement required by the simulation.

This application provides a user-friendly interface to easily set up a furnace configuration. The whole model is fully adaptable to most configurations. From the inductor electric supply circuit to the geometrical air gap size between the inductor and the crucible, most parameters are available to the user within the interface. Then, the mesh adapts itself to consider the specific requirements of the magnetic simulation field. This remeshing step is computed in a completely transparent manner for the user.

Using a 2D axisymmetric formulation, configurations can be solved to quickly provide post processing results based on concrete industrial needs, such as the power distribution in the charge or the global efficiency of the equipment.

1. Introduction

SIMTEC, as the French Leader of the COMSOL Certified Consultant, routinely develop some custom-made decision-making tools to its clients. These tools enable them to take the best decision, based on scientific results, even if they are neither expert in modelling, nor in numerical simulation. To illustrate this service, an induction furnace application is presented within this article. This application is made available to the user through a COMSOL Server™ run by SIMTEC HPC and a secured https internet connexion.

An induction furnace generally consists of three distinct parts. First, the inductor which is a coil supplied with an alternating current that causes the induction phenomenon. Second, the material to be heated or melted. This part is called the charge. The charge is therefore placed inside the inductor. Finally, a last area called the crucible contains the heated charge. This part is necessary to pour the charge when the melting is finished.

The operating principle of the furnace is as follow. The variable current in the inductor creates a variable magnetic field. Under the field impulse, an induced current appears in the electrically conductive charge. Thus, the charge heats up by Joule effect. This heating is therefore directly dependent on the geometrical and physical parameters of the furnace, such as the frequency of the inductor power supply and the conductive and magnetic properties of the charge. Another type of furnace exists, in which the crucible, often made in graphite, is heated by induction. The charge then heats up by thermal conduction.

2. Modelling

a) Geometry

To dynamically provide results, a 2D axisymmetric furnace model was chosen. The entire model can be parametrized to be as general as possible and to meet the maximum number of requests. Each

part of the furnace has its dedicated parametrization tab.

Inductor tab

The user can choose all the geometrical parameters to define the coil of their inductor. One turn of a coil is represented in 2D axisymmetric by a square or circular section, possibly hollow. The optional hollow section models a water circulation system necessary for cooling purposes. The outer part models the copper conductor in which the supply current flows. In addition, the application computes and displays the copper mass which is required by the inductor.

Crucible tab

The crucible is geometrically defined by its radius, height, and thickness. Unlike the inductor, the crucible material is variable, so it can be chosen from a drop-down list containing a predefined material library. Besides, the crucible mass is displayed as well as the current δ skin depth. This quantity corresponds to the thickness of the conductor in which the induced current effectively flows. If δ is smaller than the conductor thickness, then this means that the current is not flowing through the entire conductor. This skin effect thickness depends on the frequency of study and the conductor material. It is defined by the following relationship:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

Where f is the frequency of study and μ and σ are respectively the magnetic permeability and the electrical conductivity of the material under consideration.

Charge tab

This tab is very similar to the crucible tab. It allows the user to choose the material and the charge height you wish to heat or melt, while again displaying the melt mass and skin depth.

b) Materials

Since the crucible and the charge materials depend on the modelled configuration, the application provides a library of classical materials used in industrial induction furnace processes. Moreover, the application allows for defining two additional custom materials in this tab. They are made available for the crucible and the charge. The quantities required by the application are as follows:

- A density required to compute the masses of the different furnace areas.
- Magnetic properties (relative magnetic permeability and permittivity) to be able to write and solve Maxwell's equations corresponding to the problem.
- Thermodynamic properties (melting temperature, mass heat and fusion enthalpy) useful for assisting the furnace design which will be detailed later.

Material	Density	Relative permeability	Relative permittivity	Electrical conductivity $[S.m^{-1}]$
Copper	8960	1	1	$5.998e^7$
Quartz	2600	1	4.2	$1e^{-12}$
Structural steel	7850	1	1	$4.032e^6$
Aluminium	2700	1	1	$3.774e^7$
Gold	19300	1	1	$45.6e^6$
Silver	10500	1	1	$61.6e^6$
Graphite	1950	1	1	3000
Silicon carbide	3200	1	10	1000

Table 1 - Default materials electromagnetic properties

Material	Melting temperature $[^\circ C]$	Mass heat $[J.kg^{-1}.K^{-1}]$	Latent heat of fusion $[kJ.kg^{-1}]$
Copper	1084	385	397
Quartz	-	820	-
Structural steel	-	475	-
Aluminium	660	900	208
Gold	1064	129	64.9
Silver	962	235	103
Graphite	3527	710	-
Silicon carbide	2650	1200	-

Table 2 - Default materials thermodynamic properties

c) Electromagnetic Field

The electromagnetic field $(\vec{E}, \vec{B})$ is solved using a frequency domain study in COMSOL Multiphysics®. The Maxwell equations are solved using the vector potential $\vec{A}$ [1]:

$$\nabla \times \vec{H} = \vec{J}$$
$$\vec{B} = \nabla \times \vec{A}$$

$$\vec{B} = \mu_0\mu_r\vec{H}$$
$$\vec{E} = -j\omega\vec{A} - \vec{\nabla}V$$
$$\vec{J} = \sigma\vec{E} + j\omega\vec{D}$$
$$\vec{D} = \varepsilon_0\varepsilon_r\vec{E}$$

where μ_r is the relative permeability, ε_r the relative permittivity, $\omega = 2\pi f$ the pulsation, σ the electrical conductivity and $\vec{J}$ the current density. The equation is solved under its 2D axisymmetric form.

d) Model-circuit coupling

To assist the furnace design, the 2D axisymmetric inductor model is coupled to a user selected RLC circuit, which models the furnace power supply circuit. Several types of supply are therefore available in the application. First, a series RLC circuit for its simplicity, but also two parallel RLC circuits which are closer to the reality of many industrial induction furnaces.
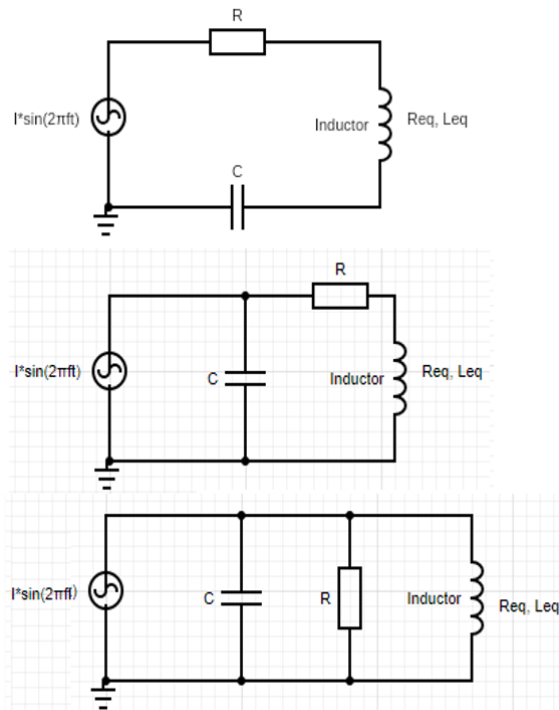

Figure 2 - Available RLC power supply circuits (here: current, but tension based power supply can also be used)

R and C values are editable. Besides, the generator can either apply a current (Cf. Figure 2) or a tension. The circuit coil, which represents an equivalent model of the furnace model, is represented by an inductance L_{eq} and a resistance R_{eq} placed in series. The furnace power supply (sine supply, defined by a frequency and a peak value) can also be edited. The inductor is modelled using the "Single conductor" coil component in the COMSOL AC/DC module. This component models any kind of conductor in which a current flows freely due to the material's conductivity. Thus, it is highly adapted to the inductor model to account for proximity effect.

3. Resolution
a) Hardware

COMSOL Multiphysics® 5.5 software is used to build and solve the numerical system defined previously. On a 2.80GHz processor with two cores used for the resolution, the resolution takes up to fifteen seconds to run. It means the application can be used interactively without significant delay.

b) Smart Meshing

As the numerical solution of Maxwell's equations is based on a finite element method, the 2D domain must be meshed properly. When modelling an electromagnetic phenomenon, it is crucial to correctly mesh the areas of interest. A common rule of thumb is to ensure that there are two or three layers of mesh in the thickness, with 2nd order elements. The application is able to adjust this criterion automatically in the charge, the crucible and the coil. Each time a parameter is modified, the skin effect is recalculated, then the domain is re-meshed accordingly. If necessary, a "Boundary Layers" mesh is used to ensure that the mesh has three layers in the skin depth. The rest of the thickness is meshed with triangular meshes.

The inductor also has a refined mesh because the copper wire thickness is often narrow. Moreover, it is an area of interest. The rest of the field of study is meshed using a coarser default triangular mesh proposed in COMSOL Multiphysics®.

4. Design assistance
a) Circuit coupling

The coupling of the finite element model with an electrical circuit makes it easy to give the user crucial information. To do this, the characteristic quantities of the circuit obtained after resolution are computed, i.e. once the values L_{eq} and R_{eq} are calculated.
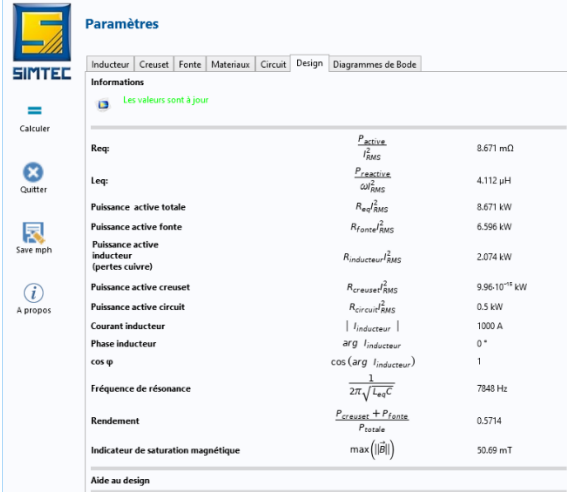
Figure 3 - View of the information display interface for the series RLC circuit

The available values are the following:

- Active power in each furnace part. Those pieces of information are computed by integrating the volumetric electric loss density on each domain of interest. Thus, a global active power can be defined with the same integrals on the whole domain of study.

- L_{eq} and R_{eq} values, which are a summary of the furnace behaviour at the considered frequency. They are computed respectively by dividing global active and reactive power by the square of the current at the terminals of the coil in the equivalent circuit.

- Since there are parallel RLC circuits available, the current at the coil terminals is different from the generator current. Thus, the effective maximum coil current value and its phase regarding the current supply are computed directly from the available coil variables

- The resonance frequency of the equivalent circuit, given by $f_0 = \frac{1}{2\pi\sqrt{L_{eq}C}}$.

- A value of efficiency r defined by the ratio between power in domains of interest (the crucible and the charge) and global power.

$$r = \frac{P_{crucible} + P_{charge}}{P_{global}}$$

- The magnetic field maximum intensity, to identify the possible occurrence of magnetic saturation, as they are not considered in our modelling.

b) Design information

To help industrials in the dimensioning of the furnace, two tools are provided in the dedicated "Design" tab. The idea is to help control the furnace power supply and to estimate the furnace quality.

The first tool allows for controlling the supply frequency according to a desired skin depth in the charge. If well chosen, this thickness allows to optimize the power distribution in the material to be melted. Thus, it accelerates the melting process. The skin depth in the charge is given by:

$$\delta_{charge} = \sqrt{\frac{1}{\pi f_{supply}\mu_{charge}\sigma_{charge}}}$$

One infers that:

$$f_{supply} = \frac{1}{\pi\mu_{charge}\sigma_{charge}\delta_{charge}^2}$$

To estimate the quality of the furnace on a specific charge material, the application also proposes an estimation of the melting time using a simple thermodynamic balance in the charge.

If one considers an initial temperature θ_0 for the material to be melted, and its melting temperature θ_{fus}:

- The energy required to heat it up from θ_0 to θ_{fus} is given by: $m_{charge}C_{p_{charge}}(\theta_{fus} - \theta_0)$
- The energy required for its fusion is given by: $m_{charge}L_{F_{charge}}$

Where m_{charge} is the mass of material to be melted, $C_{p_{charge}}$ its mass heat in $J.kg^{-1}.K^{-1}$ and $L_{F_{charge}}$ its latent heat of fusion in $J.kg^{-1}$.

Under the strong assumption that all the electrical power transmitted in the charge is used to heat the workpiece without thermal losses, the following equality is deduced:

$$m_{charge}C_{p_{charge}}(\theta_{fus} - \theta_0) + m_{charge}L_{F_{charge}} = P_{charge}t_{fusion}$$

where P_{charge} is the power transmitted by induction to the charge and t_{fusion} is an approximation of the minimum time to melt the charge. Note that P_{charge} is available in the "Circuit" tab with the other circuit information described in the previous circuit-coupling section.

Thus, the following formula estimates the melting time:

$$t_{fusion} = \frac{m_{charge}C_{p_{charge}}(\theta_{fus} - \theta_0) + m_{charge}L_{F_{charge}}}{P_{charge}}$$

Of course, not all the power is used to heat the charge as there are losses. However, this approximation gives an order of magnitude of the time needed for the furnace to perform its function.

c) Graphical results

Graphical post-processing is available to better visualise the magnetic field and the inductive power distribution in the furnace. Those graphics are provided directly in the interface. A revolution around the 2D axisymmetric axis has been used to obtain 3D views.
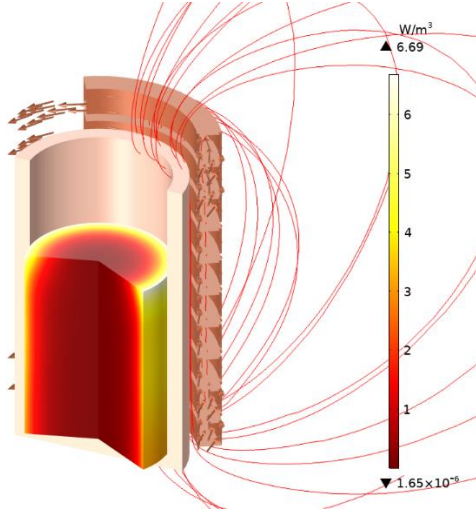

Figure 4 - 3D view of the induced power distribution in the melt

d) Bode diagrams

To complete the analysis of the equivalent RLC circuits, the application provides a tool to draw Bode diagrams associated with the circuit currently selected. These graphs allow to consult the gain and phase shift of the current at the coil terminals compared to the current supplied by the generator as a function of the supply frequency. Each point of these curves requires a frequency resolution. Thus, the plotting of these diagrams is not instantaneous.

For the parallel RLC, these curves are displayed in semi-logarithmic scale and are defined by:

$$y = 20 log_{10}\left(\frac{I_{coil}}{I_{supply}}\right) [dB]$$

and

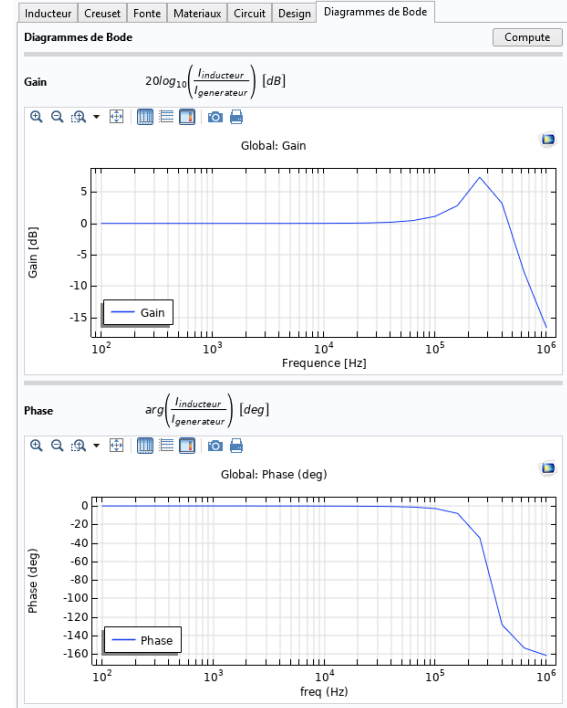$$y = arg\left(\frac{I_{coil}}{I_{supply}}\right) [°]$$

Figure 5 - Example of Bode diagrams obtained from the application for the parallel RLC circuit

For the series RLC circuit, the application displays the equivalent with the tension of the coil and the supply.

5. Conclusion

In this article, an induction furnace application is developed by SIMTEC to illustrate the possibility of easily providing a user-friendly custom-made decision-making tool. The objectives of this interactive application are to model and to design an induction furnace which is presented in this paper. Its interface provides an intuitive geometrical parametrization and materials configuration to model a large panel of furnaces. A circuit-model coupling under COMSOL Multiphysics using the AC/DC module allows to compute and display graphs and information on a simplified equivalent model. Those pieces of information give a global overview of the furnace and help to optimize its power supply. Thanks to the frequency solver used, it is possible to quickly change the configuration parameters and to get updated results interactively with minimum delay. The simplicity of the interface makes the modelling and the numerical simulation accessible to non-expert users.

References
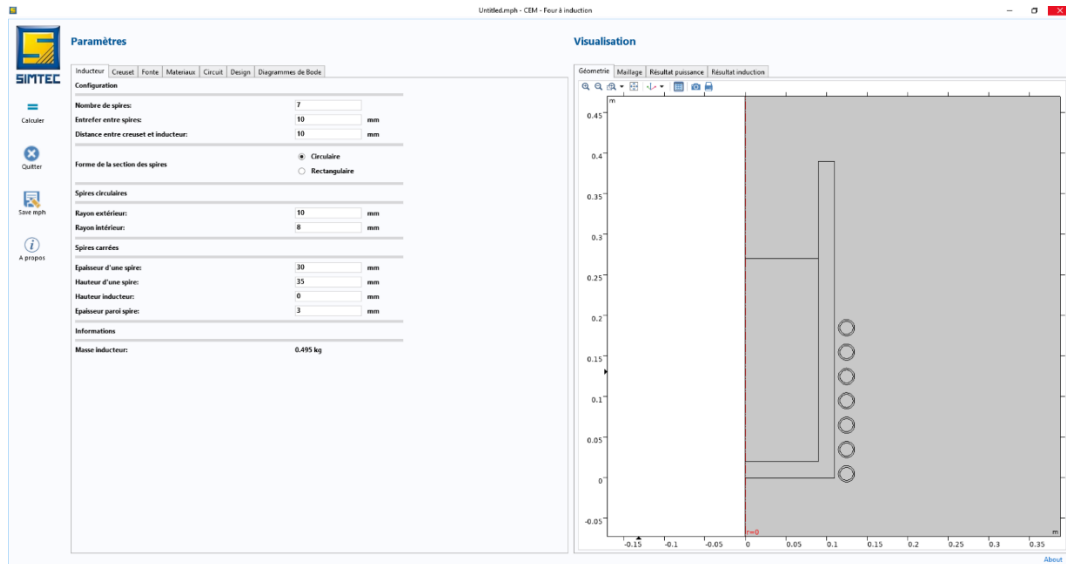
(1) COMSOL AC/DC Module User Guide

6. Annexes

Figure 6 –View of the user interface