LS-DYNA® R7: Coupled Multiphysics analysis involving Electromagnetism (EM), Incompressible CFD (ICFD) and solid mechanics thermal solver for conjugate heat transfer problem solving

Iñaki Çaldichoury (1)
Pierre L'Eplattenier (1)
Facundo del Pin (1)
Miro Duhovic (2)

(1) Livermore Software Technology Corporation
7374 Las Positas Road
Livermore, CA 94551

(2) Institut für Verbundwerkstoffe GmbH,
Erwin-Schrödinger-Str., Gebäude 58
67663 Kaiserslautern, Germany

Abstract

LS DYNA R7's new modules and capabilities include: two fluid mechanics (CFD) solvers for incompressible (ICFD) and compressible flows (CESE) and an Electromagnetism solver (EM). The objective of these solvers is not only to solve for their particular domain of physics but to make full use of LS-DYNA capabilities and material library in order to solve coupled multiphysics.

This paper will present how the EM solver can solve inductive heating problems, the problematic that arises when cooling the heated materials and/or coils is needed and how the ICFD solver can be used in conjunction in order to solve the complete EM-conjugate heat transfer problem. For illustration purposes, an industrial application studied at the Institut für Verbundwerkstoffe (See "Advances in simulating the processing of materials by electromagnetism induction" paper) will be introduced and discussed.

1- Introduction

LS-DYNA R7 double precision includes an Electromagnetics (EM) solver as well as a CFD solver for incompressible flows (ICFD). The objective of these new solvers is not only to solve for their particular domain of physics but to make full use of LS-DYNA capabilities and material library in order to solve coupled multiphysics problems. So far, several applications involving the EM solver coupled with either the solid mechanics solver or the thermal solver or both have been solved and presented in [1], [2] or [3]. On the other hand, the ICFD solver is also capable of solving Fluid Structure interaction problems (FSI) or conjugate heat transfer problems as was shown in [4], [5] and [6]. The current paper aims to bring the multiphysics concept to the next step by solving an industrial application involving Electromagnetic heating and fluid cooling. Therefore, both the EM and the ICFD solvers will be used and coupled through the LS-DYNA thermal solver.

This paper will begin by introducing the induced heating capabilities of the EM solver and the conjugate heating capabilities of the ICFD solver. It will then proceed by introducing the background of the industrial application studied and finally show the numerical model and some first results when compared to the experiment.

2- The EM solver for induced heating applications

The Electromagnetism (EM) module solves the Maxwell equations in the Eddy current (induction-diffusion) approximation [1]. This is suitable for cases where the propagation of electromagnetic waves in air (or vacuum) can be considered as instantaneous which is the case in most industrial magnetic metal welding, forming or inductive heating applications. The EM solver is coupled with the structural mechanics solver (the Lorentz forces are added to the mechanics equations of motion), and with the structural thermal solver (the Ohmic heating is added to the thermal solver as an extra source of heat) thus allowing the simulation of moving coils and the heating or deformation of work pieces. The EM fields are solved using a Finite Element Method (FEM) for the conductors and a Boundary Element Method (BEM) for the surrounding air/insulators. Thus no air mesh is necessary.

Among its various features, the EM solver in LS-DYNA includes an inductive heating solver. It was introduced in order to solve the computer cost issue arising when high frequency currents, thus very small time steps, were combined with long simulation runs (typically, an AC current with a frequency ranging from kHz to MHz and a total time for the process in the order of a few seconds). The induction heating solver works the following way: it assumes a current which oscillates very rapidly compared to the total time of the process. The following assumption is made: a full eddy-current problem is solved over two full periods with a "micro" EM time step, see Figure 1.

An average of the EM fields during the full period as well as the joule heating is computed. It is then assumed that the properties of the material (heat capacity, thermal conductivity, magnetic permeability) and mostly the electrical conductivity which drives the flow of the current and the joule heating do not change for the next periods of the current within the “macro” EM time step chosen. As all the properties are largely temperature dependent, the assumption can therefore be considered accurate as long as the temperature does not change too much. During these periods, no EM computation is performed; only the averaged joule heating term is added to the thermal solver. However, as the temperature and thus the electrical conductivity changes together with all the other material properties mentioned, the EM fields need to be updated accordingly so another full eddy current resolution is computed for a full period of the current giving new averaged EM fields (introducing a “macro” EM time step). In this way the solver can efficiently solve inductive heating problems for both the cases of a static or moving coil. In the present paper, it will be used in order to simulate the heating of a coil.

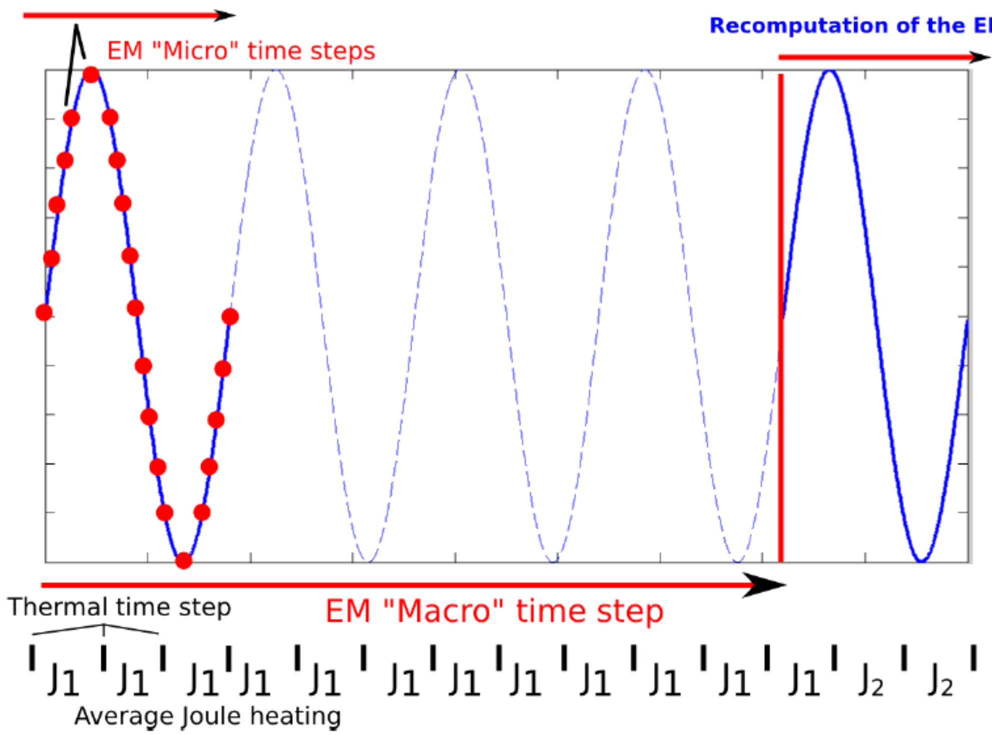

Figure 1 Graphical representation of the electromagnetic field and resulting joule heating calculation scheme implemented in the LS-DYNA inductive heating solver

3- The ICFD solver for conjugate heat transfer applications

Heat transfer is a discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy and heat between physical systems. By solving the heat equation, the ICFD solver offers the possibility to solve and study the behavior of temperature flow in fluids. Potential applications are numerous and include refrigeration, air conditioning, building heating, motor coolants, defrost or even heat transfer in the human body. In the current paper, it will be used in order to solve the coil cooling.

For the thermal coupling between the heat equation solved by the thermal solver in the structure and the heat equation solved in the fluid by the ICFD solver, a monolithic approach has been adopted. The coupling between the structure and the fluid is therefore very tight and strong at the fluid-structure interface. The resulting full system includes both the structural and the fluid temperature unknowns (See Figure 2) and is solved using a direct solver which is very robust but may in some cases be computer-time consuming.

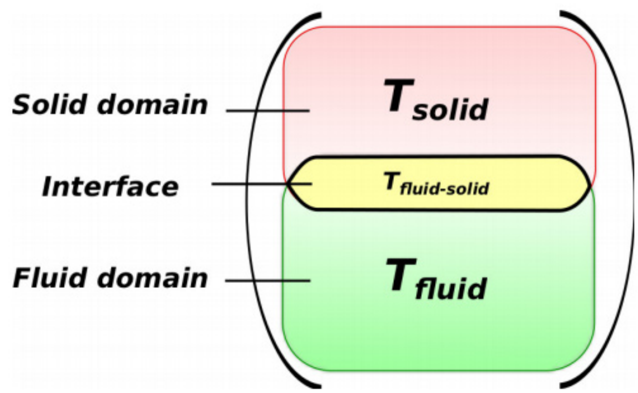

Figure 2 Vector of temperature unknowns when the fluid thermal solver and structure thermal solvers are coupled using a monolithically approach.

4- Joining and welding applications using induced heating

As the requirements for lightweight designs keep increasing in the automotive industry, the use of thermoplastic based composite materials for welding and joining during the vehicle body construction will become more and more frequently encountered (See Figure 3).

The technology to provide quick and efficient joining by robotic means for both metal to composite and composite to composite thermoplastic parts has been in development at the Institute für Verbundwerkstoffe (IVW) over the last 15 years, in the form of robotic composite welding through electromagnetic induction.

Indeed, it is now known that in woven carbon fiber reinforcement structures, eddy current joule heating can produce enough heat in the composite to allow for thermal bonding to occur without the use of susceptors. With the correct selection of electromagnetic, thermal and mechanical parameters the composite can be melted precisely in a small volume of material close to the bond line so that the two parts can be joined effectively without any detrimental effects of overheating and deconsolidation.

In order to study different parameter set ups and in order to predict the heating of workpieces by moving coils, the EM solver is being used. An example of such a study can be seen in Figure 4. Further results and examples of the uses of the EM solver for solving such induced heating applications can be found in [7] and [8].

The only physics currently missing from the current numerical simulations is fluid dynamics and the cooling of the coil. Indeed, during the experimental set-up, a cold water flow passes through the sparse coil in order to maintain the coil temperature at acceptable levels. Without this cooling process, the coil would certainly melt. It is therefore of particular interest to be able to simulate and correctly predict the behavior of the cooling process in order to prevent potential damages to coils and work tools.

Figure 3 ***Examples of automotive components that could or have already benefitted from induction welding (left). Induction welding Kuka robot at the Institute für Verbunwerkstoffe (right) joining the two thermoformed components of the BMW M-series front bumper beam***

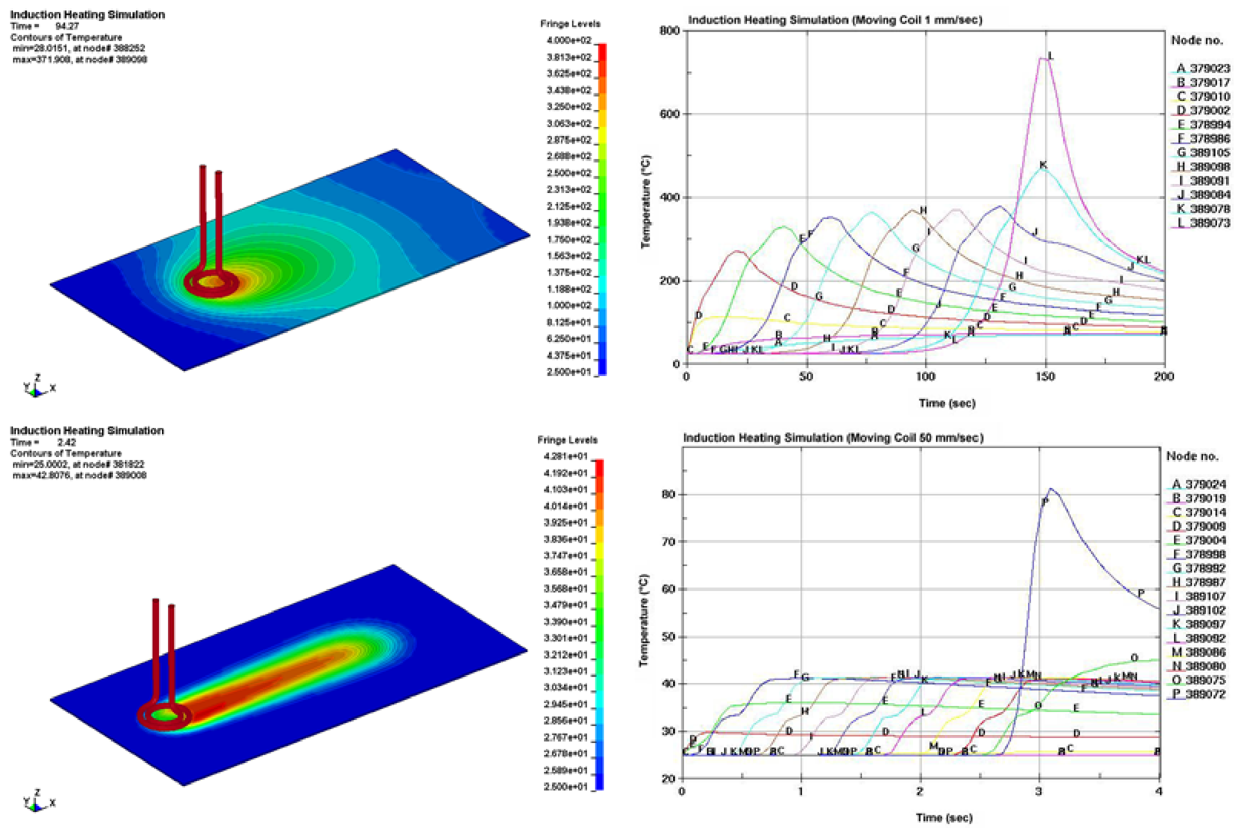

Figure 4 Graphical representation of the electromagnetic field and resulting joule heating calculation scheme implemented in the LS-DYNA inductive heating solver

5- The coupled EM-thermal-ICFD model

5.1 EM-thermal simulation

For this work, a "pancake" coil geometry will be used with an approximate radius of 0.05 m. The tube diameter of the coil is approximately 8 mm and its sparse inner radius (through which the coolant is supposed to flow) is of 6mm. Its material is copper and its structural, thermal and electrical properties are given in Table 1. The mesh size considered through the thickness of the coil is approximately 0.6 mm (See Figure 5).

During the preliminary tests, an EM-thermal only problem was run with a current frequency of 289 kHz and an Amplitude of 394.85 A. The influence of temperature on the electrical conductivity is taken into account. As could be expected, the maximum coil temperature rises quickly and reaches over 1085°C at its central area after only 15 seconds which is the coil's melting point (See Figure 6). This justifies the use of a water flow though the coil for cooling purposes.

Table 1 Coil physical parameters

Density	8960 kg/(m^3)
Heat Capacity	385 J/(Kg.K)
Thermal Conductivity	390 W/(m.K)
Electrical Conductivity	5.998e7 S/m

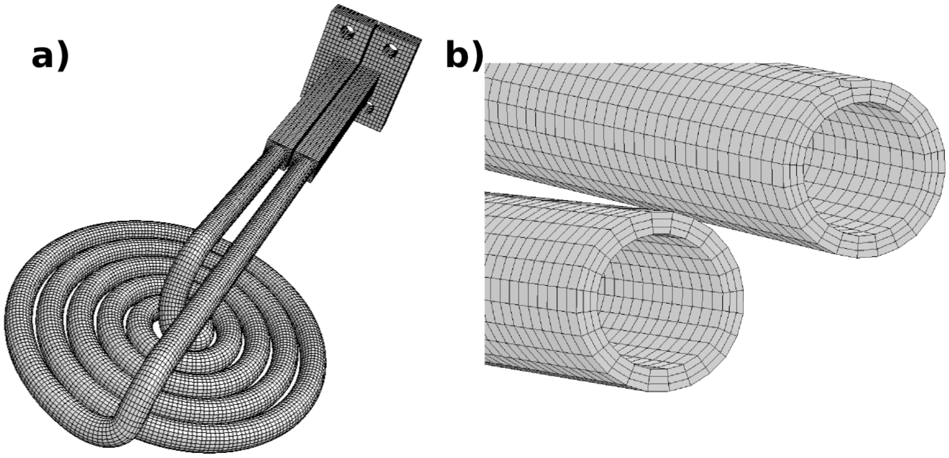

Figure 5 Coil geometry and mesh. a) Global view, b) Zoom on inner section

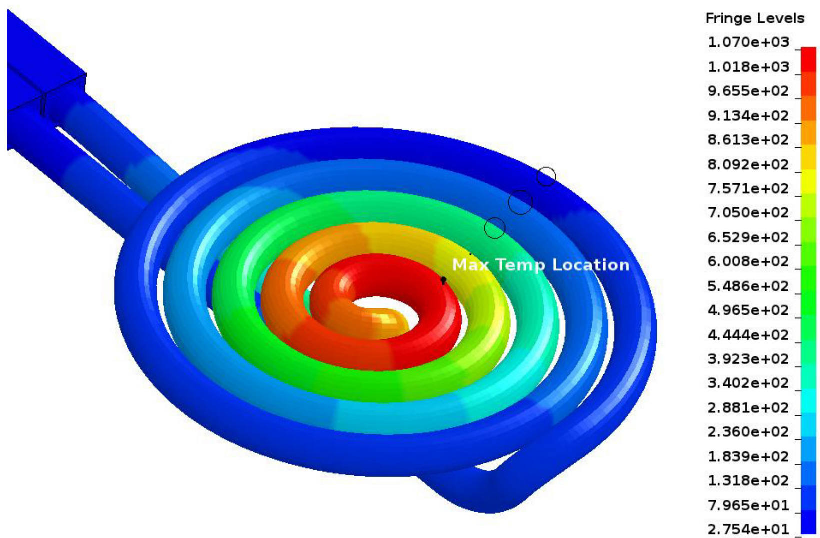

Figure 6 EM-thermal only maximum temperature increase after 15 seconds at 394.85 A

5.2 Adding ICFD coupling

For the ICFD model, the mesh size used will be approximately 0.6 mm with four elements added in the anisotropic direction of the boundary layer which results in about 10 elements through the thickness of the pipe and 1.5 M elements in the fluid volume mesh (See Figure 7). The inlet velocity corresponds to a flow rate of 1 l/min with a temperature of 23 degrees. The thermal properties of the liquid will be those of water. The water flow will be directed from the center outwards. We will work under the assumption that the flow is laminar.

The effects of the coolant can be quickly observed as the coil's temperature now reaches equilibrium instead of continuously rising. In Figure 8a), it can be observed that the correct representation of the boundary layer is of tremendous importance since the temperature diffusion gradient in the fluid seems to be located primarily in that zone. The good behavior of the conjugate heat transfer solver can be further noted when comparing the temperature fringes between the solid and the fluid that are consistent at the interface even if the geometries do not match perfectly (See Figure 8 b)). Qualitatively, it can be observed that the temperature is at its highest point at the center of the coil. This is consistent with the experimental images extracted from a thermal camera that show a high temperature zone at the coil's center (See Figure 9).

In the ICFD coupled model, the EM solver is switched off after 8 second as steady state has been reached and therefore this source of heat is removed. Consequently and in accordance with the experimental behavior, the coil starts cooling. A comparison between an experimental point taken in the hottest zone of the coil and its numerical equivalent shows the good agreement between the experiment and the simulation (See Figure 10).

As a conclusion, it seems possible to track down the effects of cooling on the coil's temperature through the use of the combined LS-DYNA EM-thermal-ICFD solvers. Further tests will be conducted at various current frequencies and amplitudes in order to confirm the observed consistent behavior.

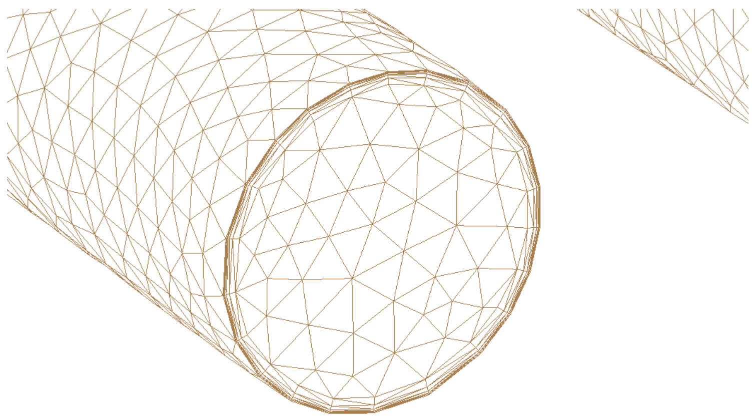

Figure 7 Fluid mesh: zoom on the inflow section

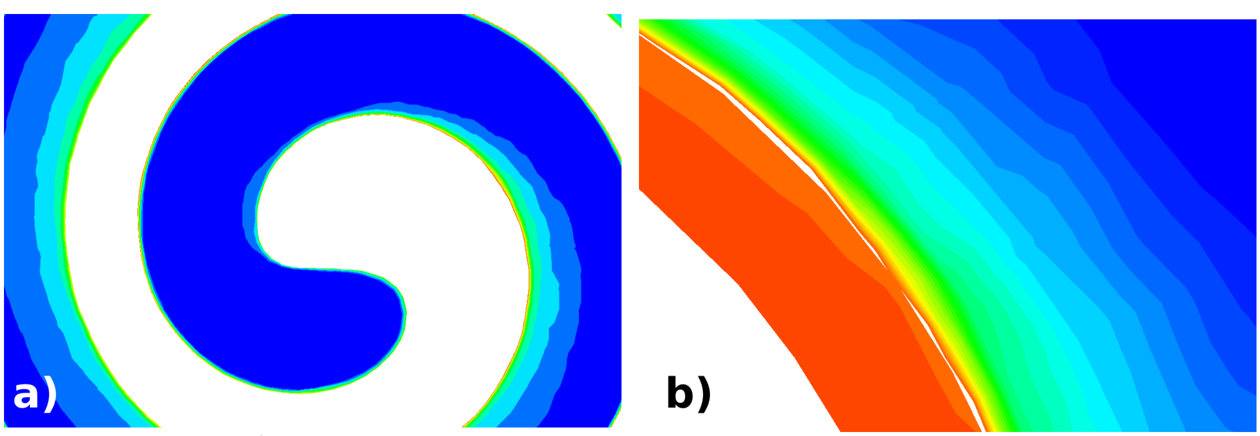

Figure 8 Temperature fringes : a) Fluid only, zoom on central part. b) Fluid and structure zoom on coil section

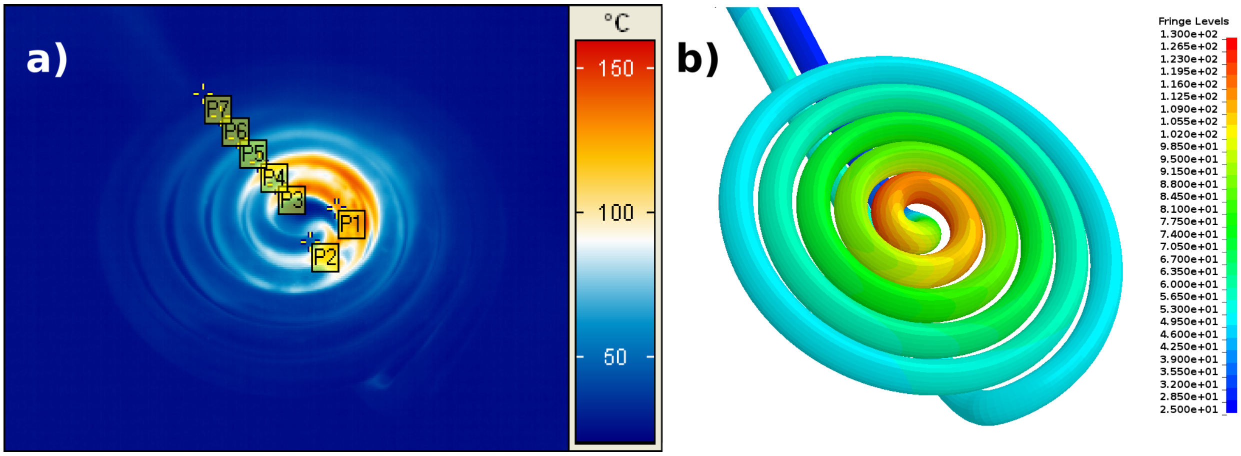

Figure 9 Comparison for coil temperature between a) Experimental results from thermal camera, b) Numerical simulation results

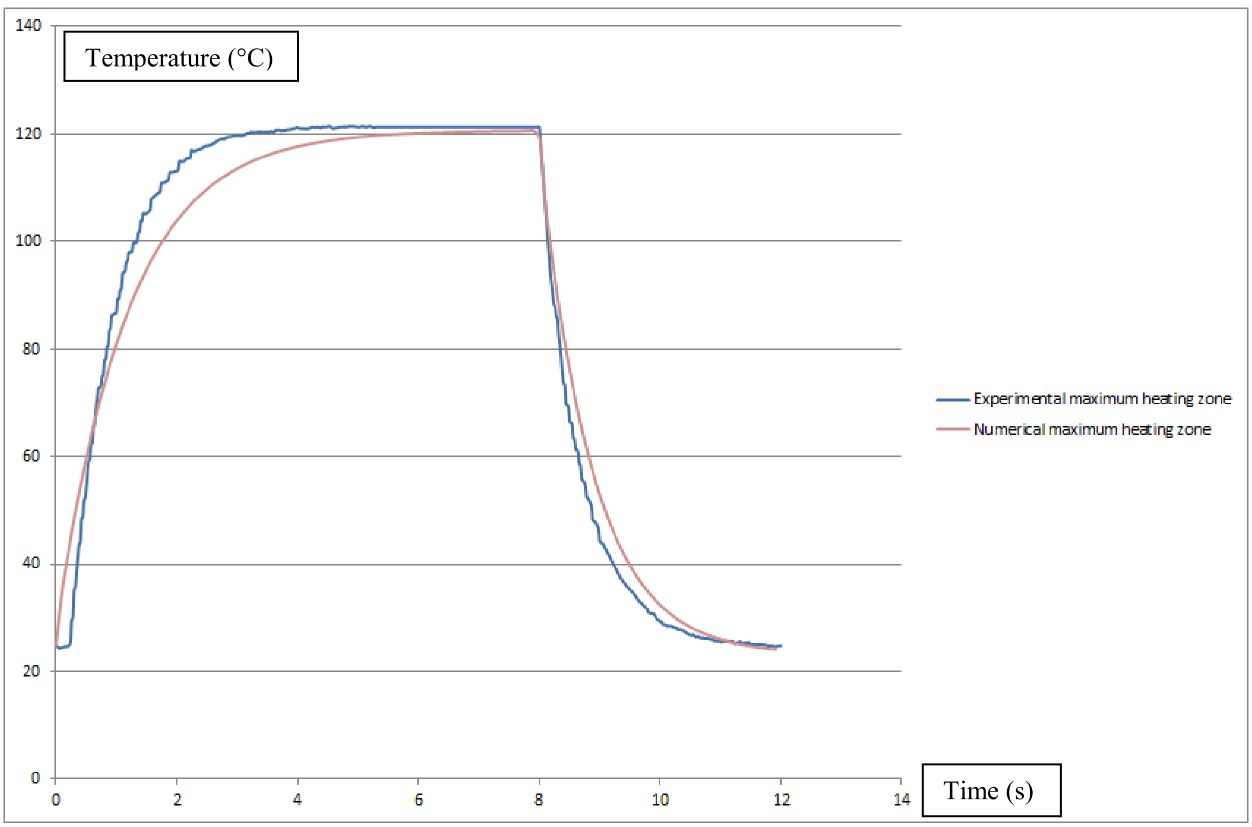

Figure 10 Heating and cooling. Temperature behavior: comparison between experimental point p1 and equivalent numerical location

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