# Magneto-Thermal Analysis of aWireless Power Transfer System

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***Abstract*—In the paper, a magneto-thermal analysis of a static Wireless Power Transfer System (WPTS) is performed. The analysis is based on the Finite Element Method coupling the two field problems. A prediction of the temperature increase in the car frame is accordingly calculated.**

***Keywords—WPTS, magneto-thermal analysis, finite element model, thermal measurements***

## I. INTRODUCTION

Static Wireless Power Transfer Systems (WPTSs) are an alternative technology to charge the onboard batteries of electric vehicles (EVs) instead of the classical plug-in solutions. WPTS uses the magnetic induction to charge onboard car batteries [1].

The WPTS devices are based on a pair of coils separated by an air gap [2]. The ~~fixed~~ transmitting coil is buried under the road surface and supplied by a power generator, and the receiving coil, is mounted under the car frame. In general, in a static WPT device the transmitting coil is buried in the parking pitch, then the onboard battery is charged while the car it is parked.

The static recharge requires a careful positioning of the vehicle on the parking pitch in order to assures the alignment between the two coils ~~maximizing~~ to maximize the mutual inductance.

The transmitting coil is supplied by a current at 85 kHz as suggested by SAE standard [3]. The variable magnetic field ~~at 85 kHz~~ generates eddy current in the steel car frame and could increases its temperature. In fact, a typical charging process lasts a few hours and therefore the thermal behavior of WPTS cannot be overlooked.

The issue of the thermal behavior of WPTS for electric vehicles is still largely unexplored; in fact, in literature, there are only a few papers dealing with prediction of the temperature increase [4]. Moreover, the SAE standard recommends to the manufacturers the evaluation of the car frame heating [3]. ~~The~~ This paper aims to contribute to fill this gap by developing a FEM model of the coils of WPTS, performing a thermal analysis on it, and comparing the obtained results with experimental data.

Specifically, in the paper, the pair of coils is simulated in three different positions in order to evaluate the power induced in the car frame during the static recharge and the related temperature increment due to eddy currents. A fully aligned coils case and a couple of unaligned case are evaluated. The same geometry was used to solve both an electromagnetic problem and a thermal problem. The thermal problem uses as input the power in the inductor and the one due to eddy currents in car frame computed solving the electromagnetic problem.

## II. FINITE ELEMENT MODEL

### *A. Geometry of the problem*

The 3D Finite-Element Model (FEM) of the WPTS device in Fig. 1 is formed by a transmitting and a receiving coil with 15 turns. Each coil is provided with a ferrite layer. The vehicle frame is a modeled as a 0.7 mm thick steel sheet, sized 800 mm x 800 mm as suggested by SAE standard. Between the ferrite and the car frame is inserted an aluminum shield to limit eddy current in the steel layer. The discretization of a thin layer at 85 kHz requires the generation of a large number of mesh elements (in the order of $10^9$) to evaluate the eddy current in the penetration depth (that is in the range of 20 μm) with a high computational cost. In the presented model, the steel sheet and aluminum sheet are both modeled as surfaces and discretized by means of 2D shell elements. This way, the mesh size is drastically reduced to 4’421’900 second order volume elements for the electromagnetic problem.

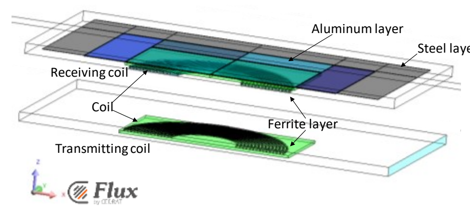



Fig. 1 Electromagnetic problem domain for WPTS.

The thin region is treated with the magnetic scalar potential formulation, $\phi$, and ~~computes~~ the difference between the value of the magnetic field on the two sides of the sheet is computed by resorting to an analytical formulation that describes the eddy currents by an exponential law. This approach, known also as the “shell formulation”[5], requires that the thin sheet is surrounded only by a non-conductive region.

As described in [6], the field model is coupled with a circuit model that includes the two coils, an ideal current source and a resistive load, which represent the battery, as well as the resonance capacitor connected to the receiving coil.

The same geometry was used to solve both an electromagnetic and a thermal problem. The thermal problem domain considers a subset of the volumes of the electromagnetic problem and then the mesh has only 1’775’600 second order volume elements. In particular, the domain includes receiving coil, ferrite, steel and aluminum layers placed on a vetronite layer. The coil is in contact with the ferrite layer by means of the insulating sock made of glass fiber. A particular of the mesh is in Fig. 2.

Both the electromagnetic and thermal problems were implemented and solved using Flux 3D, a commercial software licensed by Altair, USA [7].

The electrical (resistivity, $\rho$ and relative magnetic permeability, $\mu_r$) and thermal properties (thermal conductivity, $h$, heat capacity, $c_p$, material density, $d$) of the materials are listed in Table I.

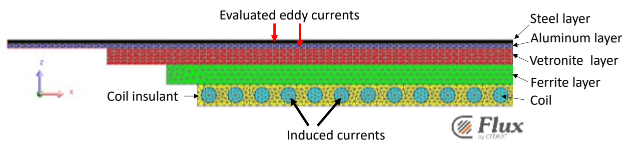



Fig. 2 thermal problem domain and mesh detail

Table I electrical and thermal properties of materials

| | $\rho$ [$\Omega$m] | $\mu_r$ [NU] | $h$ [Wm$^{-1}$K$^{-1}$] | $c_p$ [Jkg$^{-1}$K$^{-1}$] | $d$ [kg m$^{-3}$] |
|---|---|---|---|---|---|
| Steel | $60\cdot10^{-8}$ | 10 | 26 | 460 | 7700 |
| Aluminum | $2.65\cdot10^{-8}$ | 1 | 235 | 937 | 2700 |
| Ferrite | NC | 3000 | 4 | 700 | 4800 |
| Vetronite | NC | 1 | 0.3 | 1200 | 1800 |
| Sock | NC | 1 | 1 | 958 | 2480 |
| Copper | $1.68\cdot10^{-8}$ | 1 | 394 | 393 | 8960 |

*NU= not unit, NC= non-conductive

### B. *Electromagnetic problem*

The FEM solves a steady state AC magnetic problem through the scalar magnetic potential and vector electric potential formulation, coupled with the external electrical circuit. The computational domain is represented in Fig. 1. The FEM model was used to compute relevant lumped parameters like self and mutual inductances to evaluate resonance capacitor to supply the device and to transfer a suitable power to the load [8]. Finally, the current in the receiving coil and also the eddy current loss, which are both the sources of the thermal problem, are calculated.

### C. *Thermal problem*

The temperature increase in the car frame was evaluated using FEM and solving a steady state heat problem. Because of the assumption of linear magnetic and thermal materials, a standard coupled-field formulation was solved. The thermal problem should be subdivided into two sub-problems i.e. the inverse problem of identifying the heat exchange coefficient $h$ by natural convection, based on thermal measurements done with a thermal imagining camera. In turn, the forward problem can be read as follows: given the $h$ coefficient, find the temperature map in the thermal domain shown in Fig. 2. At a first glance, the boundary of the domain was considered as a surface that exchanges heat with the environment at 20°C with a convective exchange coefficient $h$ equal to 10 Wm$^{-2}$K$^{-1}$, because the suggested range for the heat exchange with still air is 5-10 Wm$^{-2}$K$^{-1}$. In the full-length paper the forward problem will be solved with the newly identified coefficient $h$.

## III. Results

Fig. 3 shows the temperature maps in the car frame evaluated considering a current amplitude in the transmitting coil of 7.2 A. The corresponding receiving coil current resulted of 15.2 A and the power transferred to a load of 5.6 Ω was 620 W, suitable to charge the battery of a minicar [9]. A Joule power loss of 58 W was estimated in the receiving coil by the induced current and considering a 0.5 Ω resistance for the coil.

The simulated highest temperature difference between center and boundary is about 18 °C.

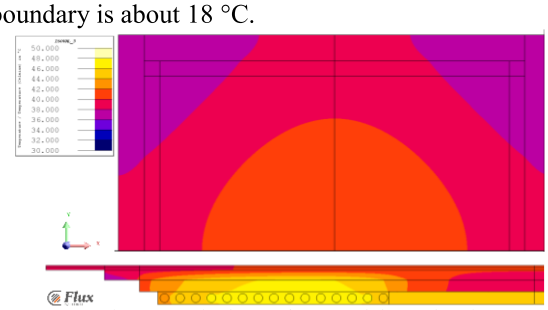
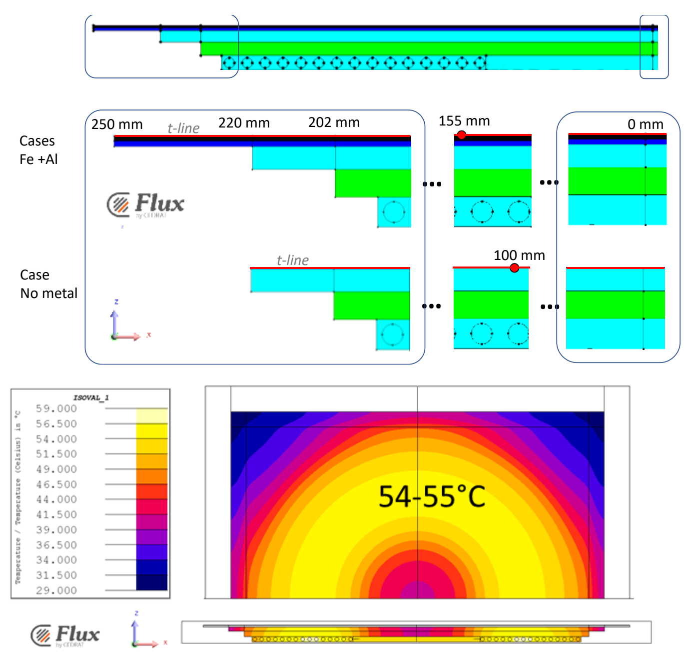
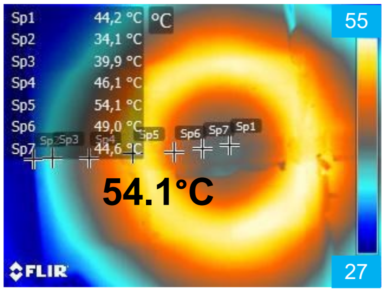
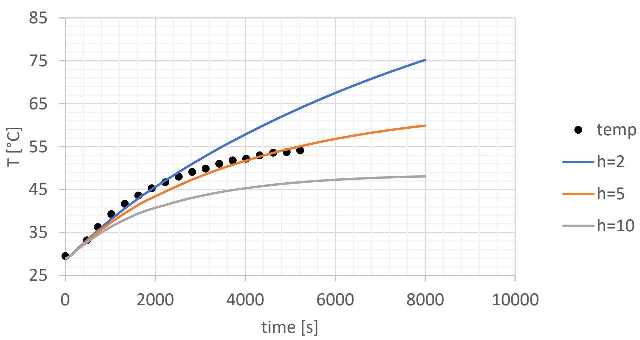
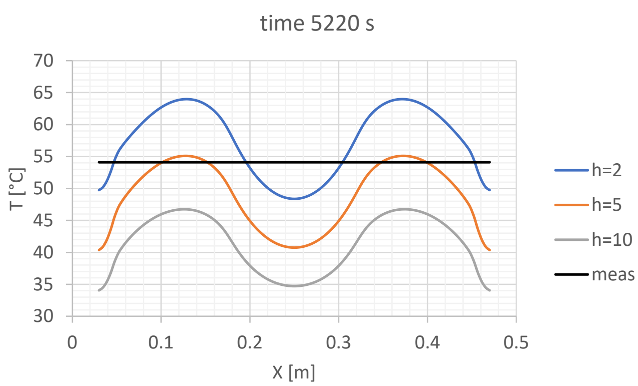


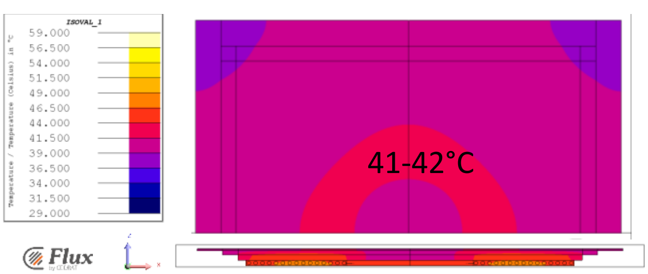
Fig. 3 Temperature increment in the car frame and thermal regions

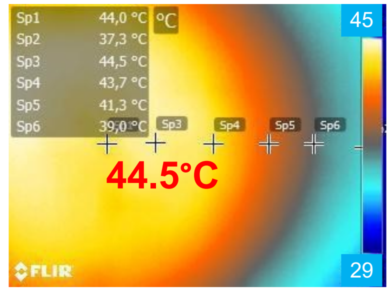


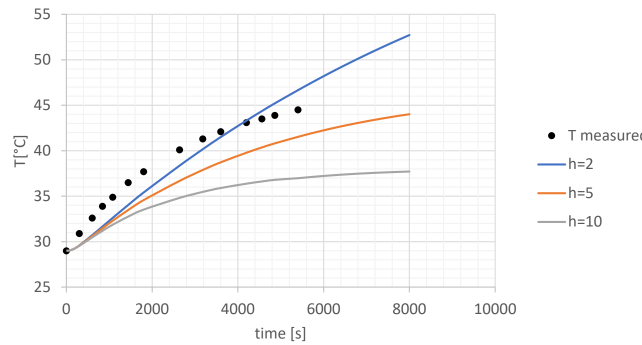


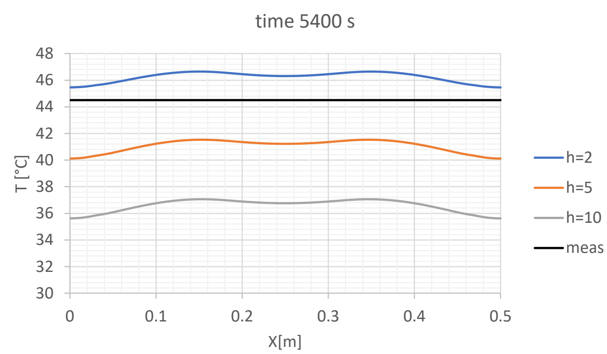




## IV. Conclusion

In the full-length paper, results of the thermal model with the *h* coefficient identified after thermal measurements will be presented. Moreover, as far as the thermal measurements are concerned, the imaging will provide us with a regional map of temperature while the assessment of the hot spot will be done by means of thermo-couple measurements.

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