

## COMPARISON OF FLUID HEATING ELEMENT MATERIALS BY ELECTROMAGNETIC INDUCTION

PEREIRA, Paulo Tibúrcio<sup>(1),(2)</sup>, MAIA, Cristiana Brasil<sup>(2)</sup>, CABEZAS-GÓMEZ, Luben<sup>(3)</sup>

<sup>(1)</sup>DETEM, CAP, Universidade Federal de São João Del Rei,  
Rodovia MG-443, km 7, Ouro Branco, Brasil

<sup>(2)</sup>PPGEM, Pontifícia Universidade Católica de Minas Gerais,  
Av. Dom José Gaspar, 500, Belo Horizonte, Brasil

<sup>(3)</sup>EESC, Universidade de São Paulo,  
Av. Trabalhador São-carlense, 400, São Carlos, Brasil

**ABSTRACT.** In this work a study was carried out aiming to the comparison of different materials of the fluid heating element by the process of electromagnetic induction. It was sought to identify the material that provides the greatest efficiency in the conversion of electric energy to thermal energy. For this, some samples of electrically conductive materials were chemically characterized. An electronic circuit was developed to energize the inductor. A sample holder was prepared in order to keep the sample inside the inductor with the temperature sensor. Measurements of RMS voltage, RMS electrical current and temperature were performed. It was found that the carbon sample showed the best efficiency in the heating process. Regressions of the measured temperature values were performed in order to identify the best equations and their coefficients. The curves of type MMF (Morgan Mercer Flodin) showed good adaptation to the temperature increase of the samples.

### INTRODUCTION

The humanity needs an increasing amount of usefull energy. Due to the scarcity and high cost of usefull energy it becomes important to minimize the losses in the energy conversion processes. In this scenario, in order to reduce energy losses, new and more efficient conversion processes are emerging. Among the new processes, the heating of fluids using electromagnetic induction is emphasized [1]. The heating of fluids by electromagnetic induction come to supplement the current need for more efficient energy conversion processes [1]. In this case, elements are required that are heated by electromagnetic induction and the heat is transferred to the fluid by the convection process [1-2]. In this work, it is sought to identify the best constituent chemical composition of the heating element in order to improve the efficiency in the process of heating fluids by electromagnetic induction.

### THEORETICAL BASE

In the process of heating fluids by electromagnetic induction can be used as heating element a electricity conductive duct or a insulating duct with a conductive material inside [1-2]. The process of heating by electromagnetic induction involves electromagnetic and thermal parameters, several of which are interrelated [1-4].

The power density generated by induction can be calculated using differential equations 1 and 2 together with 3 [5].

$$(j\omega\sigma - \omega^2\varepsilon)A + \nabla \times (\mu^{-1}\nabla \times A) = \frac{\sigma V_{loop}}{2\pi r} + J_e \quad (1)$$

$$\nabla \times E = -\frac{\partial \nabla \times A}{\partial t} = -\frac{\partial B}{\partial t} = -j\omega \nabla \times A \quad (2)$$

$$Q = \frac{1}{2} \sigma |E|^2 \quad (3)$$

The equation 1 is a Maxwell equation, also called the Ampère circuit law. It is in the complex form that is appropriate for time-harmonic electromagnetic fields (when they have a sinusoidal variation in time) and also written as a function of the vector magnetic potential. Where  $A$  is the vector magnetic potential,  $\omega$  is the angular frequency,  $\sigma$  is electrical conductivity,  $\varepsilon$  is the electrical permittivity, and  $\mu$  is the magnetic permeability,  $V_{loop}$  is the potential difference for a revolution around the  $z$  axis, used in the model with axial symmetry and  $J_e$  is the maximum density of current in the inductor.

The equation 2 is another Maxwell equation, called the Faraday law. With it one can calculate the intensity of the electric field  $E$ . The induction heating is obtained using equation 3. Where  $Q$  is the value of the power density developed in the sample.

To compare the heating elements, cylindrical samples of electrically conductive materials were chosen. The chosen materials have a high thermal conductivity and the temperature sensor was placed near the side surface of the cylindrical samples. Under these conditions, the temperature variation in samples  $\Delta T$  can be estimated using the energy conservation equation 4 [3], [6].

$$Q \approx m \cdot c \cdot \Delta T \quad (4)$$

Where  $m$  is the mass of the sample and  $c$  is the specific heat.

### SAMPLE CHARACTERISTICS

The samples were: HCS (High Carbon Steel) - SAE/AISI 1070, LCS (Low Carbon Steel) - SAE/AISI 1005, Aluminum 6351 and Carbon M 5 with dimensions 100 x 30mm.

The steel samples were characterized using SEM (Scanning Electron Microscope) manufactured by Philips model FEI QUANTA 400, WD-XRF (Wavelength Dispersive X-ray Fluorescence) manufactured by Shimadzu model XRF-1800 and the ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) manufactured by Varian model VARIAN VISTA MPX. The most significant chemical components that were found in the steel samples are shown in Table 1.

Table 1: main chemical components of steel samples [%]

	<b>Fe</b>	<b>C</b>	<b>Mn</b>	<b>Si</b>	<b>P</b>	<b>Others</b>
<b>HCS</b>	98.393	0.70	0.67	0.19	0.015	0.032
<b>LCS</b>	99.470	0.04	0.34	0.09	0.013	0.047

The characteristics of the samples of Aluminum 6351 and Carbon M 5 are indicated in Table 2 and 3.

Table 2: chemical composition of Aluminium 6351 [%] [7]

Al	Si	Mn	Mg	Fe	Others
96.75	1.00	0.60	0.60	0.50	0.55

Table 3: properties of Carbon M 5 [8]

<b>Composition</b>	97% Carbon
<b>Maximum grain size</b>	5.0 $\mu$ m
<b>Porosity</b>	10%

The electromagnetic and thermal parameters of the samples are shown in Table 4. It is observed that Carbon and Aluminum are Paramagnetic.

Table 4: electromagnetic and thermal properties of the samples

	$\rho_E$ [ $\Omega$ m]	$\mu_r$ [-]	$\rho_d$ [ $\text{kg}/\text{m}^3$ ]	$c_p$ [ $\text{Ws}/\text{kgK}$ ]	$K$ [ $\text{W}/\text{mK}$ ]
<b>C</b>	1.5e-6 [8]	1 [2]	1900 [8]	710 [10]	81.41 [8]
<b>Steel</b>	$\approx 1.0\text{e-}7$ [9]	120-2000 [9]	$\approx 7800$ [9]	$\approx 460$ [6]	$\approx 45.0$ [6]
<b>Al</b>	2.92e-8 [10]	1 [2]	2710 [7]	879 [7]	184 [7]

## THE ELECTRONIC CIRCUIT

To feed the inductor a DC/AC conversion [1] was performed using the IGBT (Insulated Gate Bipolar Transistor) IXGH 40N60B, manufactured by Ixys, polarized as class C amplifier. The IXGH 40N60B has the maximum parameters  $V_{CES} = 600\text{V}$ ,  $I_{C25} = 75\text{A}$ ,  $V_{CE(SAT)} = 2.1\text{V}$  and  $t_{fi} = 180\text{ns}$ . It was controlled with a 91kHz square wave without offset having 10.5V peak to -10.5V peak and duty cycle of 50% from a function generator manufactured by Agilent model 33210A. The Figure 1 shows the electronic circuit.

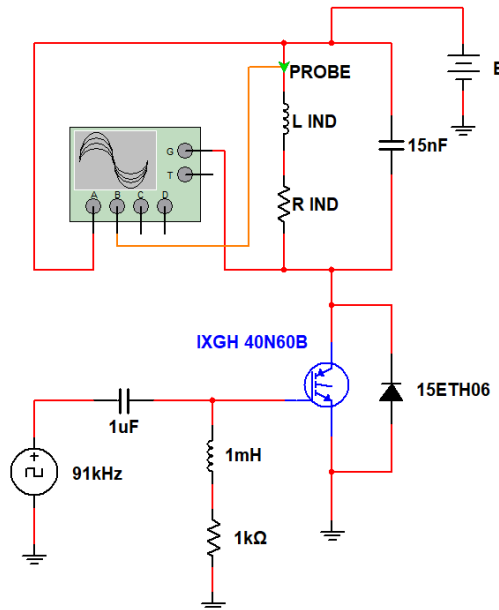


Figure 1. the electronic circuit

The series feed resonant tank circuit [1] worked at 75W and 91kHz. A mica capacitor with 15nF and 1200V insulation was chosen and the inductor was made with 6 AWG wire having 24 turns. The Figure 2 shows the resonant tank circuit with the conductive material sample inserted into the inductor. To verify the behavior of samples at temperatures above 180°C, a sample holder with thermal insulation is required to protect the electrical insulation of the inductor.

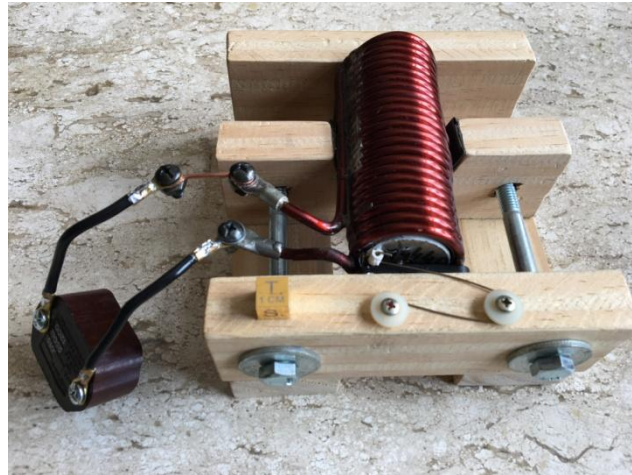


Figure 2. the resonant tank circuit and the sample holder

The RMS voltage and RMS current in the inductor were monitored to work with constant real power in all samples. For this, an digital oscilloscope manufactured by Agilent model DSO-X 2014A (100MHz, 2GSa/s) was used. The oscilloscope was equipped with a X10 voltage probe manufactured by Agilent, model P6139 (50MHz, 10M $\Omega$  with 8.0pF) and an X10 current probe manufactured by Tektronix, model P6022 with bandwidth of 935Hz to 120MHz. A transformer was used for galvanic isolation of the oscilloscope feed.

Figure 3 shows the RMS voltage and RMS current in the inductor with the LCS steel sample inserted. In this case, a sampling rate of 250 MSa/s was used.

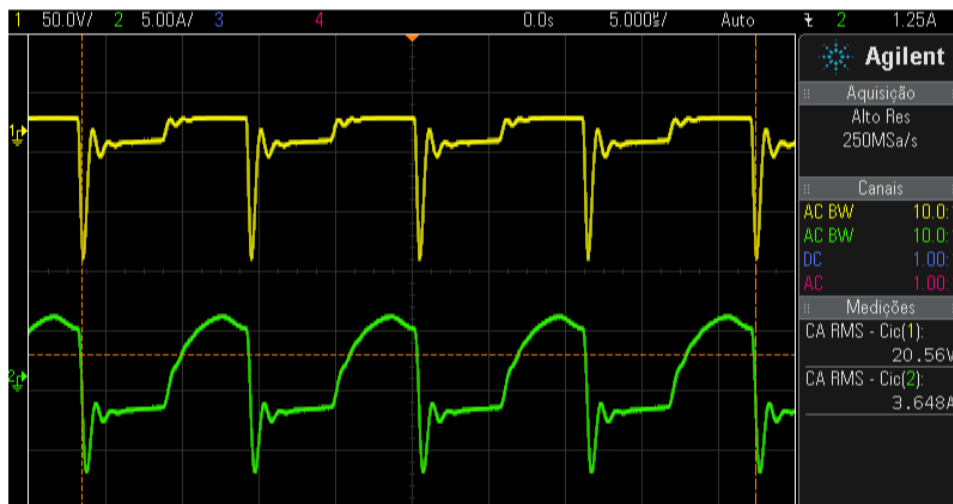


Figure 3. the RMS voltage and current in the LCS sample

The Table 5 shows the voltages and electric currents used in the samples.

Table 5: the RMS voltages and currents in the samples

	<b>C</b>	<b>HCS</b>	<b>LCS</b>	<b>Al</b>
$E_{RMS}$ [V]	18.90	20.44	20.56	17.45
$I_{RMS}$ [A]	3.97	3.67	3.65	4.30

## RESULTS

The energy conversion efficiency was verified by increasing the temperature in the samples. The temperature in the samples was monitored with a two channels datalogger thermometer manufactured by Icel model TD-880. The type K thermocouple probe was used with silver thermal paste to aid in thermal coupling. The sample temperature was measured at the cylinder base near the side surface subtracting the ambient temperature. A measurement of temperature per second was performed, totaling 900 temperature measurements per sample.

Regressions of the measured values were performed. Curves of type MMF (Morgan Mercer Flodin), equation (5), showed good adaptation to the temperature increase of the samples.

$$T = \frac{ab+ct^d}{b+td} \quad (5)$$

where  $T$  is the sample temperature rise in [ $^{\circ}$ C] and  $t$  is the time in [s].

The Figure 4 shows the curves of the values measured with their respective regressions.

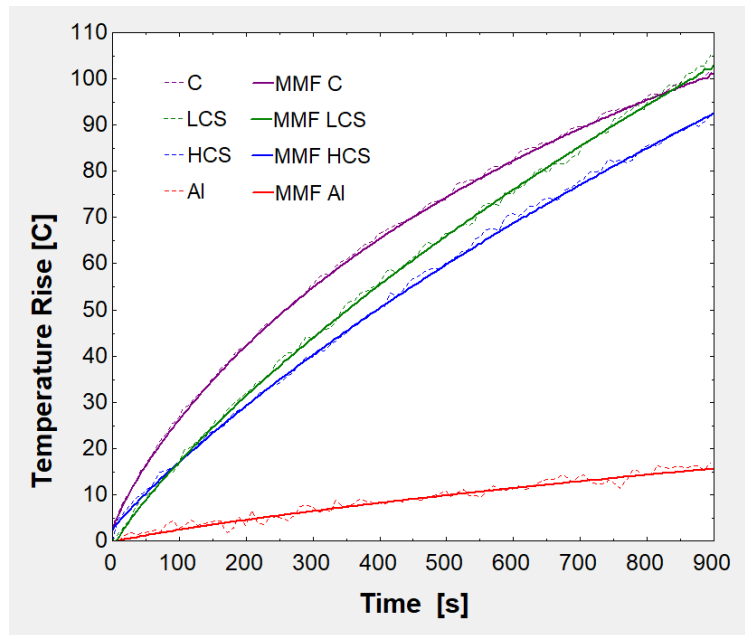


Figure 4. temperature rise in samples

The Table 6 shows the coefficients of the MMF equations that relate the temperature increase in the time course for the HCS and LCS steels, Carbon and Aluminum.

Table 6: the coefficients of the MMF equations

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
<b>C</b>	2.293762	425.608949	231.643130	0.848692
<b>ATC</b>	2.329466	1994.368082	465.304787	0.908348
<b>BTC</b>	-1.876511	1689.800588	695.864393	0.837645
<b>AI</b>	-3.306077	2172.492730	111.042476	0.866432

## CONCLUSIONS

It was verified that the Carbon sample presented the highest temperature elevation in the first 800s reaching 100°C.

The highest temperature in the carbon sample was due to its higher electrical resistivity (1.5e-6Ω.m) than the steel ( $\approx 1.0e-7\Omega.m$ ).

The low carbon steel showed a tendency to have the highest temperature after 800s and with a temperature rise above 100°C.

Comparing the curves of the steels, it was verified that the low carbon steel had the highest temperature rise. It is believed that this was due to higher concentration of 99.470% iron in the LCS sample compared to 98.393% in the HCS sample.

As the physical dimensions of the samples, the inductor and the electromagnetic coupling are constant, it is verified that the resistivity of the carbon (1.5e-6Ω.m) and the high relative magnetic permeability of the low carbon steel (from 120 to 2000-) were the parameters of the samples that more influenced the increase in temperature.

It is intended to perform new temperature measurements using thermal insulation in the sample holder, other oscillation frequencies and other samples of carbon and steel for comparisons.

## THANKS

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