# EFFECTS OF NON-LINEAR MAGNETIC CHARGE ON INDUCTION FURNACE OPERATION DURING THE HEATING CYCLE

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**خلاصة**

أن هذا البحث هو عبارة عن دراسة لسلوك المجال الكهرومغناطيسي للفرن الحثي عندما يكون قلبه مادة مغناطيسية اخذين بنظر الاعتبار العلاقة اللاخطية لكثافة الفيض المغناطيسي $B$ المتولد في القلب الحديدي للفرن كداله للشدة المغناطيسية $H$ المسلطة على ملفاته.

بما أن كلا من الخواص ألمغناطيسيه للقلب الحديدي ومقاومته النوعية تتأثران بشدة بارتفاع الحرارة فأن الدراسة تضمنت تأثير الحرارة على كلا العاملين آنيا لتوضيح السلوك الكهرومغناطيسي للفرن خلال عملية التسخين. أن توزيع كل من كثافة التيار و كثافة الفيض و شدة المجال المغناطيسي داخل القلب الحديدي وعلى سطحه الخارجي قد تم تحديدها. وكذلك فأن توزيع الفيض المغناطيسي قد تم رسمه لدرجات حرارة مختلفة.

أن هذه الدراسة قد أظهرت أهمية تضمين اللاخطية المغناطيسية وتأثرها بالحرارة في دراسة الأفران الحثية لذا، فأنها ستكون كأساس للعمل المستقبلي الذي سيتضمن التعشيق بين التحليلات الحرارية و الكهرومغناطيسية لهذه الأفران.

## ABSTRACT

This research studying the electromagnetic behavior of the induction furnace when its core is a magnetic material taking into consideration the effect of the non-linear dependence of the magnetic flux induced in it due to the applied magnetizing force.

Since the magnetic characteristics are severely affected by temperature rise in a non-linear way, so as the specific electric resistance of the charge material, this work deals with studying the effect of temperature on the non-linear characteristics of a magnetic core simultaneously with that on the specific electric resistance to show the electromagnetic behavior of the furnace during heating operation. The distribution of the current density, flux density and the magnetizing force at different temperatures inside the furnace and on the charge surfaces are determined for different temperatures. Also the flux distribution is plotted at these cases. This study will be the base for future work on the electromagnetic-thermal coupled analysis for the induction furnace.

## INTRODUCTION

This work represents the second step of analyzing the electromagnetic behavior of the induction furnace when its core is a ferromagnetic material. The results of the first step analysis have already been published and presented on a linear induction furnace[1] using a FEM package (ANSYS 5.4). In this work the analysis is extended to take into consideration the effect of three types of non-linear relations on the furnace parameters these are:

a) The effect of the non-linearity of the permeability $\mu$ with the magnetic field intensity $H$ , or $B = \mu(H) \cdot H$ .
b) The non-linear effect of the temperature $T$ on the permeability $\mu(T, H)$ .
c) The non-linear variation of the specific electric resistance of the charge material with temperature $\rho(T)$ .

The new analysis was done using numerical technique based on a general-purpose finite element package "ANSYS 7". Two previous applications[2] are considered in order to verify the results of this work. The first example is an induction furnace with magnetic core and operating at low frequency of 60 Hz, while the second furnace using the same material as a core operating at medium frequency of 4KHz. The results obtained by ANSYS 7 show a good agreement with the published work. The magnetic material used is a carbon steel SAE 1045 (C45). The data of steel C45 are extracted from references [2],[3] & [4].

It is very interesting in this work to show clearly what is going on inside the magnetic charge of the induction furnace during its operation by studying the effect of temperature increase on the distribution of flux lines, $B, H$ & $J$ (from room temperature up to Curie temperature). Such knowledge will lead to expect the effect of non-linearity and temperature increase on Skin depth $\delta = 1/\sqrt{\varpi\mu\sigma}$ . Also, it is an important step to prepare for the electromagnetic-thermal coupled analysis, which will complete the simulation of the induction heating process to be as real as possible.

**The Magnetic Non-linearity Problem**:

When the magnetic non-linearity is considered, the conventional transient analysis method will elapse a long time to solve such problem. In FEM, harmonic analysis assumes that all quantities are sinusoidally varying, but if a sinusoidal exciting field $H$ is used, non-linearity distorts the waveforms of the flux density $B$, while considering sinusoidal $B$ will lead to a non-sinusoidal $H$ . Therefore, non-linearity cannot be included in the analysis directly and iron saturation requires special treatment. Hence, Several methods[5–9] for determining appropriate permeability have been used to make account of time variation. These methods include the use of time-averaged value of the permeability over a complete cycle. The problem can then be simplified by considering only the fundamental frequency component of $B$ and $H$ . The problem, in this case, is cast in time harmonic form with $(d/dt)$ being replaced by $(j\varpi)$. The package " ANSYS 7 " deals with this problem to investigate the accurate results[10].

Accurate data for carbon steel SAE 1045 (C45) about the dependence of its relative magnetic permeability on temperature are not readily available but it could be approximated as[4]

$$\mu_r(T,H) = 1 + (\mu_r(H)_{T=0} - 1)\cdot\left[1-(T\cdot 750^{-1})^2\right] \qquad \text{when} \qquad T < 750^oC$$
$$\mu_r(T,H) = 1 \qquad \text{when} \qquad T \geq 750^oC$$

The family of curves of $B(T,H)$ is shown in Fig. (1) for steel C45, This figure

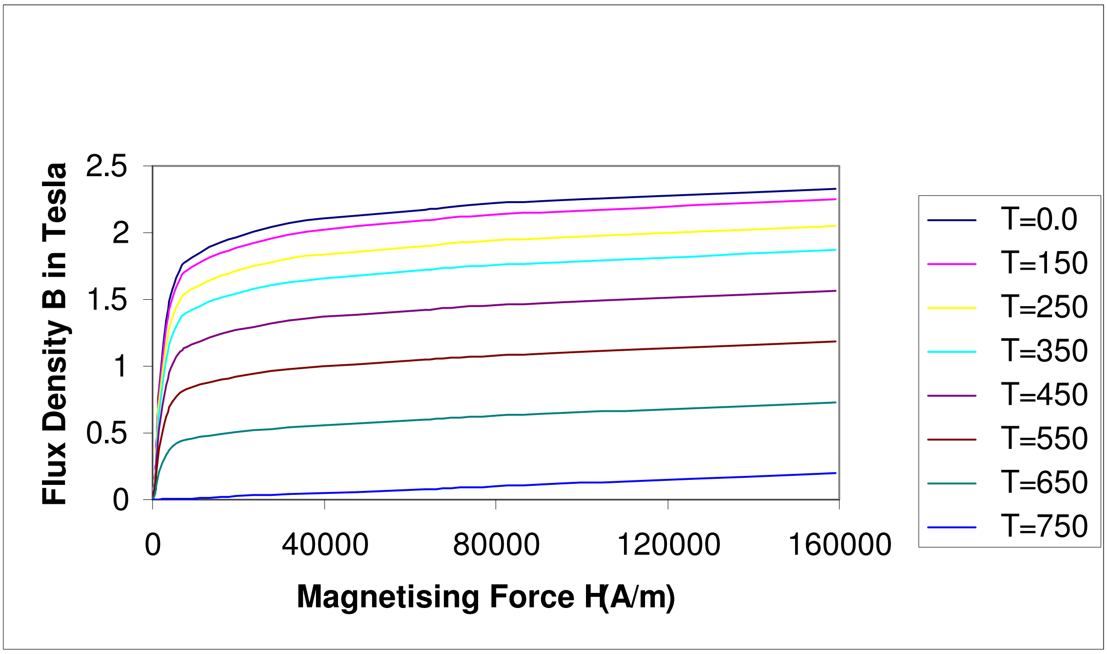



**Fig. (1)** The Magnetic Characteristics (B-H curves) for Steel C45 at different temperatures

Shows that Curie-temperature for this kind of steel is 750°C, so the characteristics at that degree is linear and $\mu_r$=1.

It is already known that the specific electric resistance of conducting materials is a function of temperature; hence, this factor should be included in this analysis in order to make the simulation as real as possible. Fig. (2) represents $\rho(T)$, the specific electric resistance or the resistively of the carbon steel C45 as a function of temperature[3].

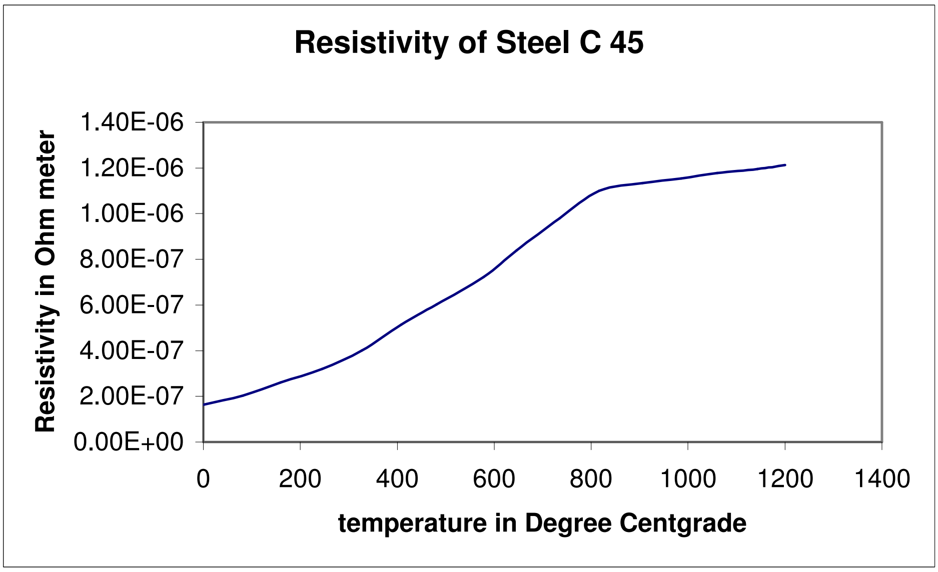



**Fig. (2)**. the electrical resistively of steel C45 as a function of temperature

## SIMULATION RESULTS

### a - Effect of non-linear magnetic charge

As mentioned before two examples have been applied to verify the present results. The first example for a low frequency furnace of 60Hz Its data shown in table (1) .

Table (1)

| | |
|---|---|
| Coil inner diameter (m) | 0.08256 |
| Coil length (m) | 0.254 |
| Number of turns | 29.5 |
| Frequency (Hz) | 60 |
| Charge material | Steel SAE1045 (C45) |
| Charge diameter (m) | 0.06032 |
| Charge length (m) | 0.254 |
| Charge conductivity (mho/m) | 5E6 |
| Relative Permeability | 18 |

In this example two solutions are obtained, (applying constant current density source), the first solution is done assuming linear magnetic material with $\mu_r$=18, and in the second solution the (B-H) non-linear relation at ($T = 0^o C$) as shown in Fig. (1) is considered. The finite element model of the furnace under consideration is shown in Fig. (3). The distribution of the normalized value of the current density magnitude $J_n = |J| / |J_{surf}|$ on charge mid-plane is drawn as a function of normalized charge radius for the linear and non-linear case is shown in Fig. (4). The results show that the current density distribution for the ANSYS and that of reference [2] are exactly the same, while, there is a difference in a nonlinear case, because they consider the non-linearity in different ways. The power loss in each case is calculated and the “Non-Linear Factor” NLF is about 1.524. Where, NLF is the ratio of the power loss inside the core in the non-linear case to that of the linear one. This computed value of NLF is about 5.4% more than Boden’s experimental value of this factor that has been found to be 1.47 [11].

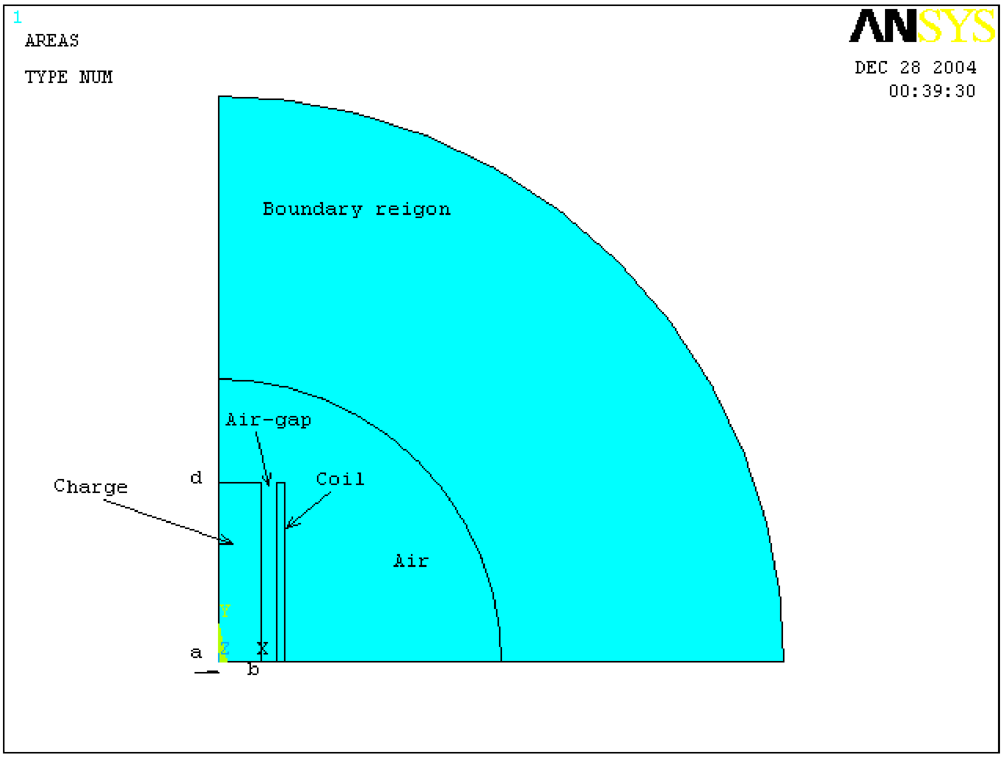



**Fig. (3).** Quarter of the longitudinal section in the finite element model of the furnace.

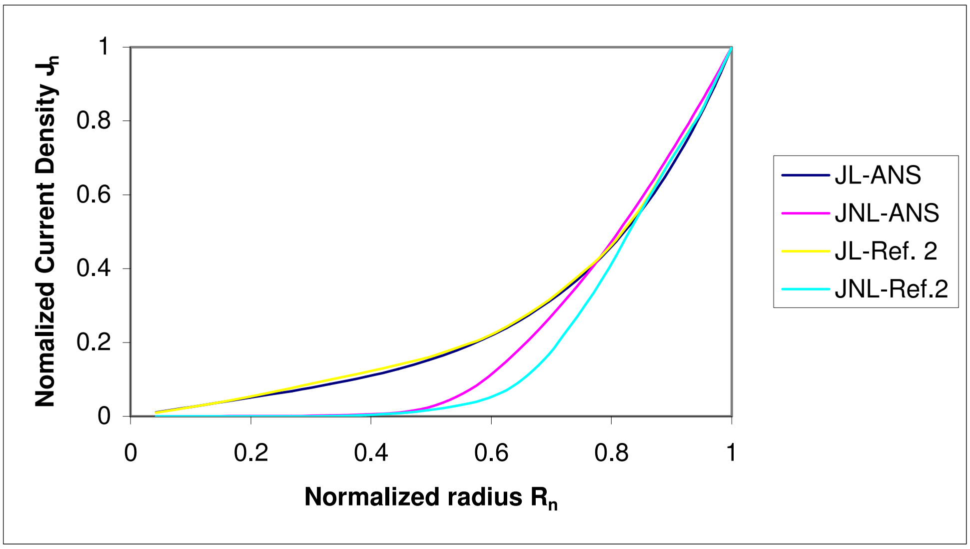



**Fig. (4)** Distribution of normalized current density magnitude for linear and non-linear cases for a 60 Hz furnace

The second example is for the medium frequency range furnace with the data shown in table (2). The same graph is drawn as that for example (1), given in Fig. (5). The results show reasonable agreement with that of reference [2]. The NLF in this case is calculated to be 1.266, which is 20.4% less than Boden's value. The obtained results verifies the method used by ANSYS 7 to treat the non-linearity of the magnetic circuit.

**Table (2)**

| | |
|---|---|
| Coil inner diameter (m) | 0.0412 |
| Coil length (m) | 0.5842 |
| Number of turns | 61 |
| Frequency (Hz) | 4000 |
| Charge material | Steel SAE1045 (C45) |
| Charge diameter (m) | 0.0254 |
| Charge length (m) | 0.5842 |
| Charge conductivity (mho/m) | 4.878E6 |
| Relative permeability | 88 |

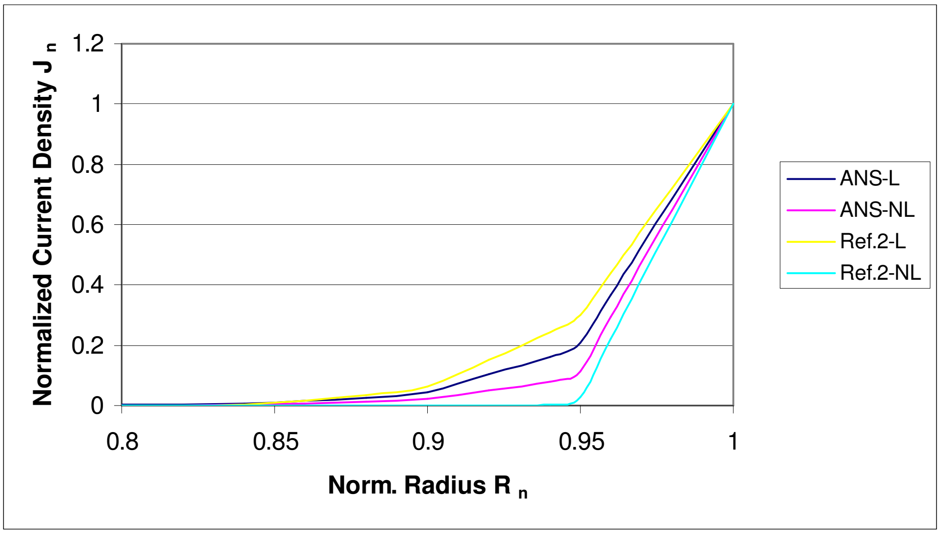
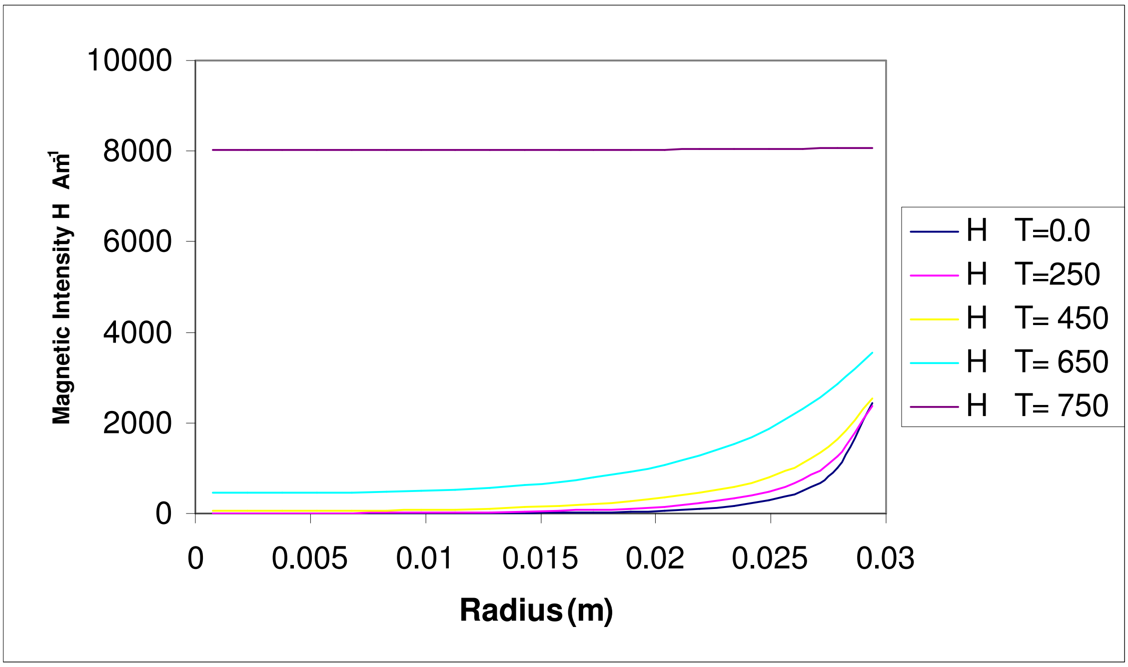


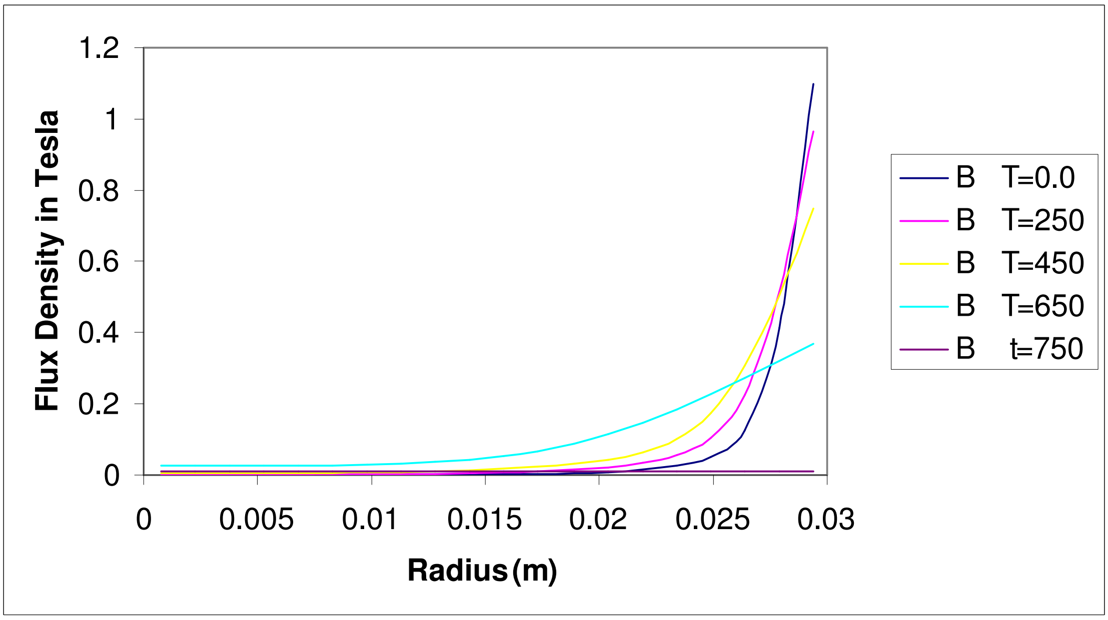

**Fig. (5)** Distribution of normalized current density magnitude for linear and non-linear case for a 4000 Hz furnace

**b- Effect of temperature increase**

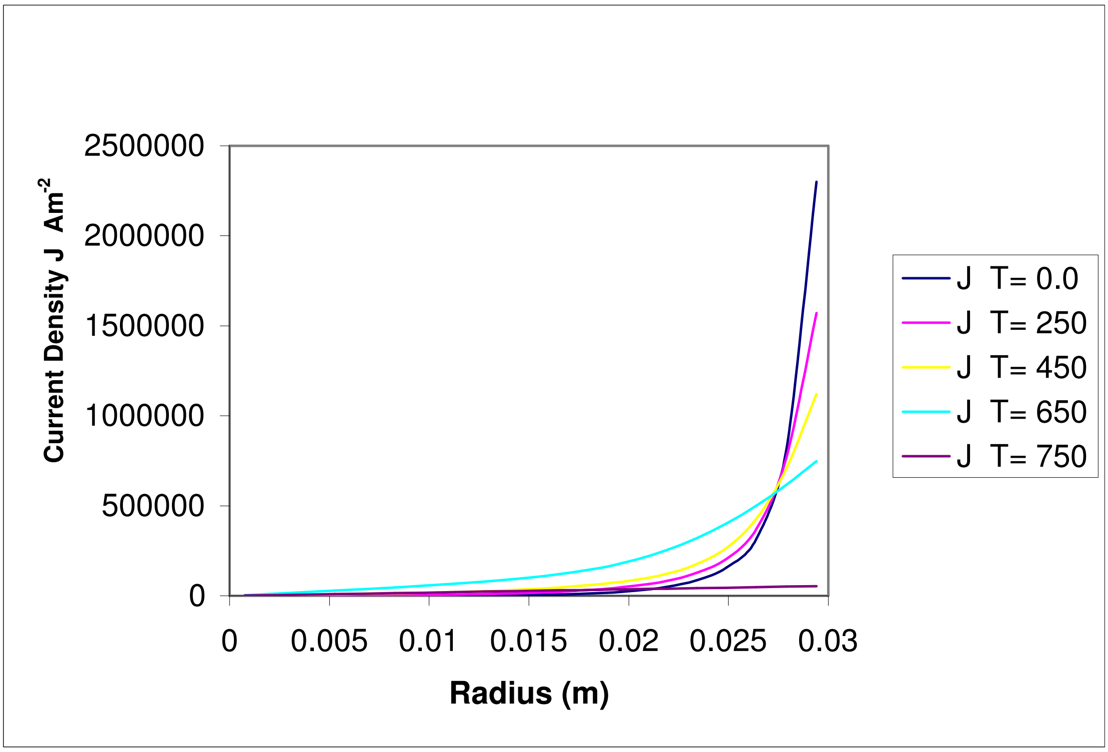
In order to study the electromagnetic parameters during the temperature increase inside the furnace, five different temperatures are assumed for the furnace under test, these are (0.0°C, 250°C, 450°C, 650°C, &750°C). The (60Hz) furnace of example (1), is analyzed at these temperatures. This analysis done on the low frequency furnace only, because, in such a kind of furnaces the heat distribution inside the core seems to be approximately uniform, so, the results will give the most logical descriptions can be obtained for the given temperature. While, this assumption is quiet wrong in the medium frequency furnaces due to the sever skin effect in such frequencies, which leads to non-uniform distribution of the temperature inside the core. The magnitudes of $H, B$, and $J$ for three different positions in the charge, (the mid-plane, the external side surface and the top surface) for each temperature are calculated and plotted as shown in Fig. (6.a.b.c), (7.a.b.c), &(8.a.b.c.) respectively.


10000
8000
6000
4000
2000
0
0
0.005
0.01
0.015
0.02
0.025
0.03
Magnetic Intensity H Am-1
Radius (m)
H T=0.0
H T=250
H T= 450
H T= 650
H T= 750

(6-a)

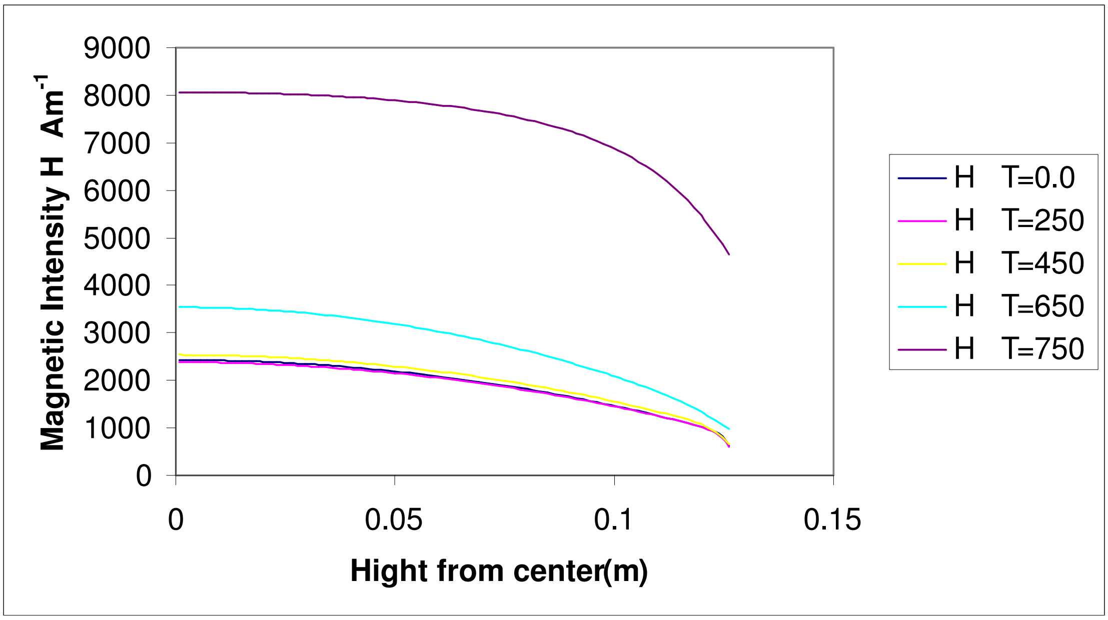

1.2
1
0.8
0.6
0.4
0.2
0
0
0.005
0.01
0.015
0.02
0.025
0.03
Flux Density in Tesla
Radius (m)
B T=0.0
B T=250
B T=450
B T=650
B t=750

(6-b)

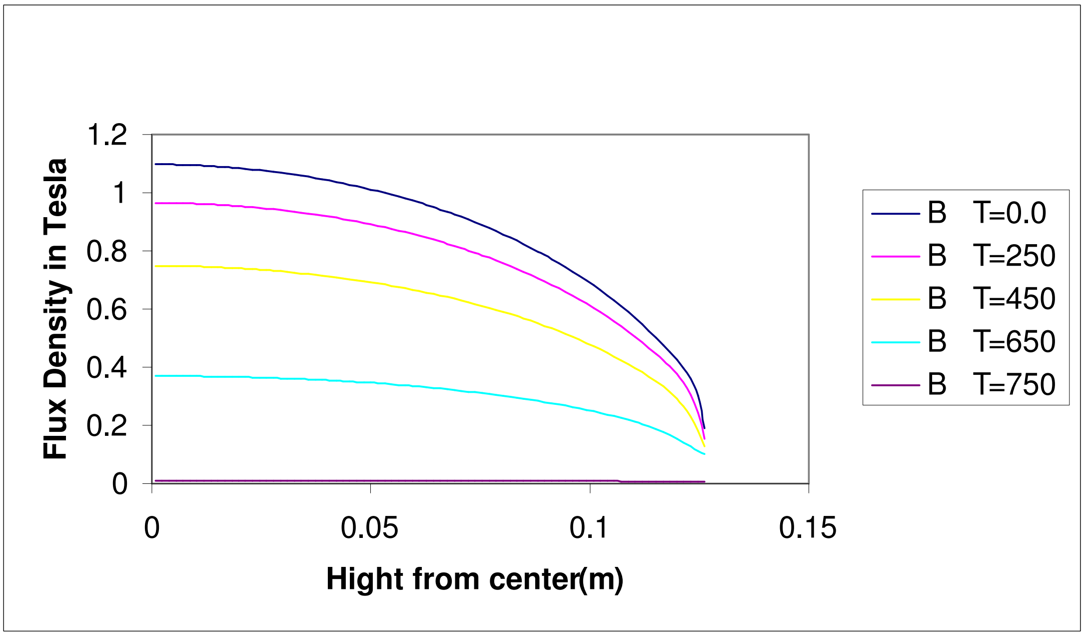



(6-c)

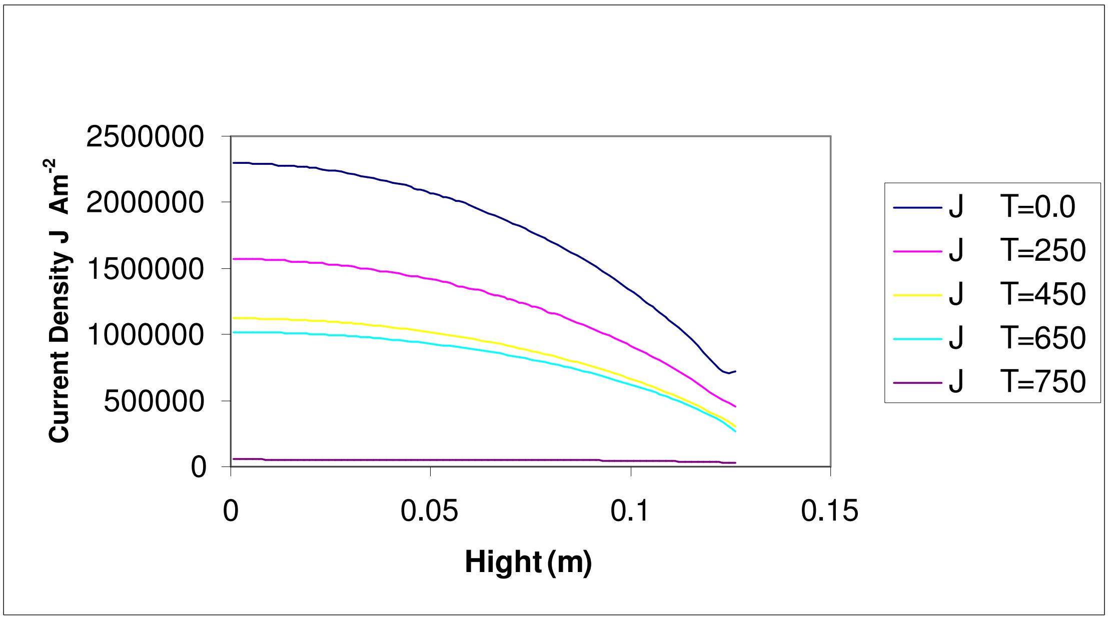
**Fig. (6-a, b, c)** Distribution of $|H|$, $|B|$, and $|J|$ as a function of the core radius in the mid-plane of the core for different temperatures


9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Magnetic Intensity H Am-1
0
0.05
0.1
0.15
Hight from center(m)
H T=0.0
H T=250
H T=450
H T=650
H T=750

(7-a)

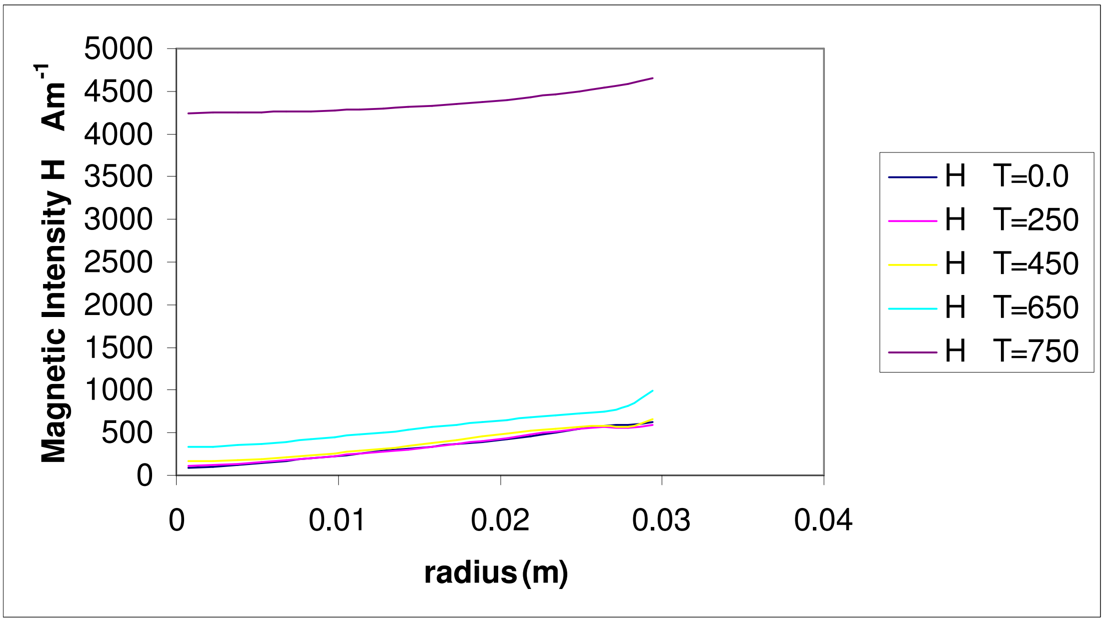

1.2
1
0.8
0.6
0.4
0.2
0
Flux Density in Tesla
0
0.05
0.1
0.15
Hight from center(m)
B T=0.0
B T=250
B T=450
B T=650
B T=750

(7-b)

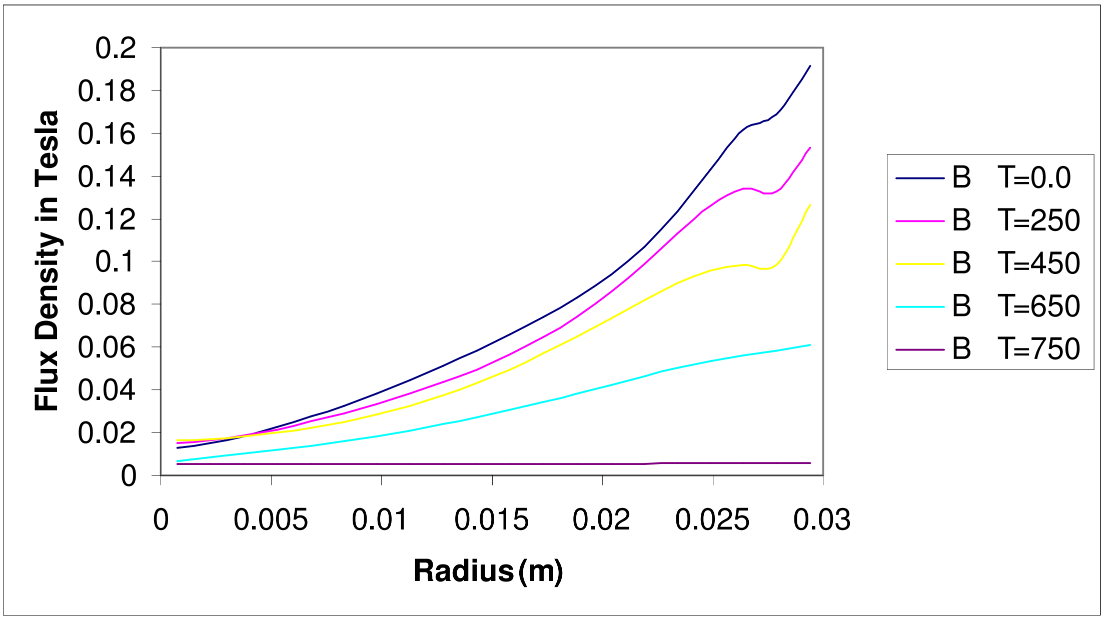



(7-c)

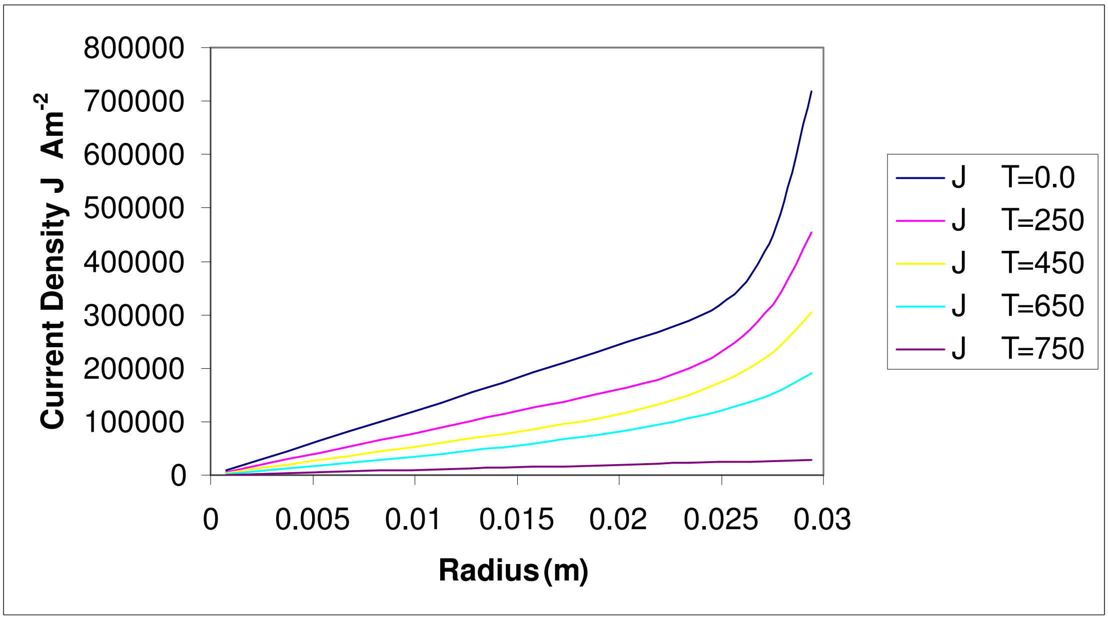
**Fig. (7-a,b,c)** Distribution of $|H|$, $|B|$ ,and $|J|$ at the external side surface for different temperatures




(8-a)




(8-b)




(8-c)

**Fig. (8-a, b, c)** Distribution of $|H|, |B|$, and $|J|$ as a function of the core radius in the mid-plane of the core for different temperatures

## DISCUSSION

This paper declares the effect of the non-linearity in the (B-H) curve of the magnetic charge of the furnace on the flux distribution and on other parameters like $J, B, \& H$. The results obtained seems to be quite reasonable, and agrees with that published to deal with non-linearity at room temperature only. Two kinds of furnaces are used for verification of the work, low frequency, and medium frequency one. The analysis extended to deal with other temperatures taking into consideration the effect of temperature increase on the permeability and the electrical resistivity of the steel charge

The results obtained in the first part of this research show that the power delivered to the charge is more than that calculated by the linear analysis, because NLF is always more than one. Also, it is clear that the skin depth is less than that in the linear case, while the eddy current magnitude increases especially behind the side external surface of the charge.

When the effect of temperature increase studied, the results show that the flux density reduced as the temperature increased due to the associative reduction in the permeability and the magnetizing force increased. This is quite reasonable because the magnetizing force is severely opposed by the flux generated due to the induced eddy currents, but, when the permeability reduced, the induced eddy currents reduced too leading to reduce the reduction of the magnetizing force. But the magnetizing force is constant since the input current to the coil from the power supply is constant, so the resultant $H$ will increase with the reduction of the permeability, which is the case here. Also, as a result of eddy current reduction, the distribution of the magnetic intensity $H$ will be approximately uniform everywhere inside the core when Curie temperature reached. This will lead to the conclusion that, the power losses due to eddy currents will be reduced with the increase of charge temperature

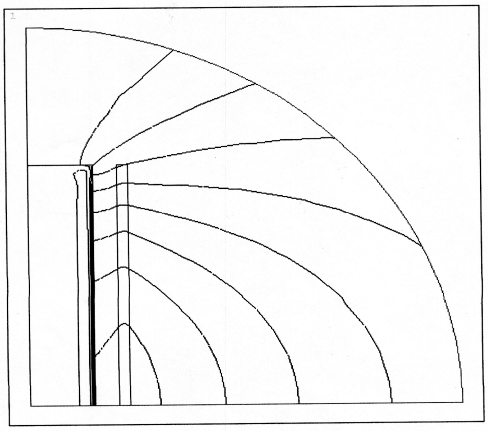
The flux distribution for each temperature is shown in Fig. (9) inside and outside the furnace. It is clear that the density of flux lines increased near the side surface of the charge at (T=0.0$^{o}$C), and it tends to be approximately uniform at Curie temperature.

## Conclusion and Future Work

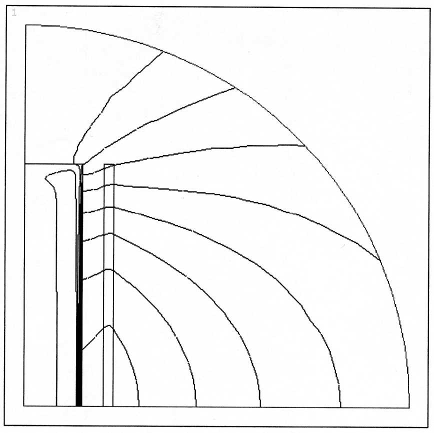
The results show that the permeability of the charge material is the dominant parameter due to its sever effect on the distribution of $J, B, \& H$, and the depth of penetration of the power inside the charge, is a function of temperature also during the heating cycle (for constant frequency).

It is very obvious that the distribution of $B, H, \& J$ is approximately uniform inside the core at Curie temperature. This study prepares to complete the simulation of the induction furnace using the FEM in that it helps to expect the furnace behavior during the heating process. In order to reach the most real study of the furnace, an electromagnetic-thermal coupled analysis should be done considering $\mu(T, H) \& \rho(T)$ simultaneously and continuously for each element inside the FE model during the increases in temperature of the furnace. Such a study will be the aim of the authors in future.

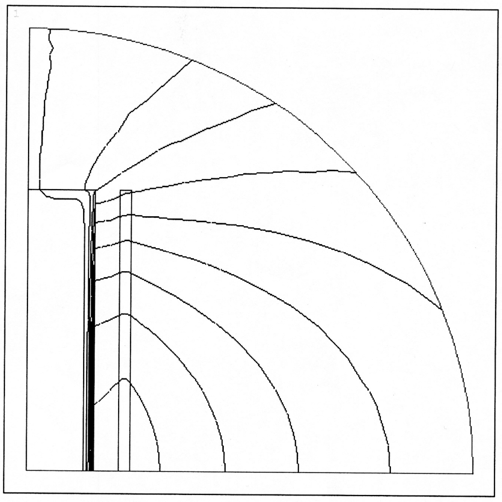
From the power supply point of view, it is clear that the furnace is a non-linear load. Hence an electromagnetic-thermal coupled analysis will lead to calculate the variation in load impedance during operation and this will help very much to expect the design parameters of the power supply needed for certain load.



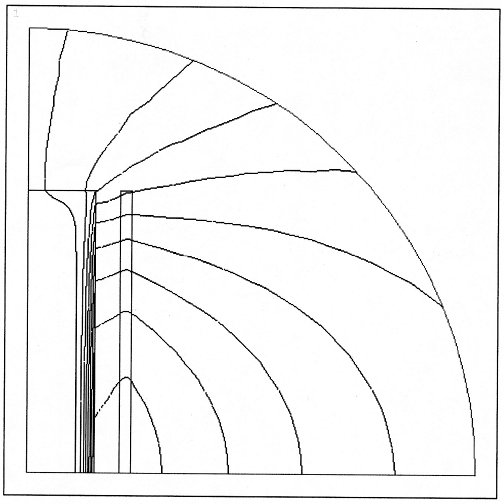
**T=0.0°C**



**T=250°C**



**T=450°C**



**T=650°C**

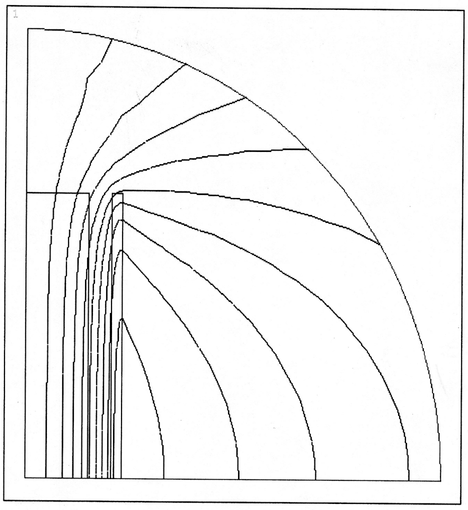


**Fig. (9)**
The distribution of flux during operation at different temperatures

**T=750°C**

$B$ : Magnetic flux density Tesla.
$H$ : Magnetic field intensity Amp.m$^{-1}$.
$I$ : Current Amp.
$J$ : Current density Amp.m$^{-2}$.
$T$ : Temperature. $^{o}C$
$\mu$ : The permeability Henry.m$^{-1}$.
$\mu_r$ : The relative permeability.
$\delta$ : The Skin depth m
$\rho$ : The resistivity Ω.m.
$\sigma$ : The conductivity (Ω.m)$^{-1}$.
$\varpi$ : The angular Frequency Rad. Sec$^{-1}$

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