Thermal Computation in Railgun by Hybrid Time Domain Technique 3-D-FEM-IEM

M. Sajjad Bayati, Asghar Keshtkar, and Ahmad Keshtkar

***Abstract*—Thermal energy in railgun is unwanted and generated by ohmic losses that are dependent to the current implied, rail dimensions, electrical conductivity (σ), and specific heat ($\mathrm{C_P}$). σ and $\mathrm{C_P}$ are functions of temperature. Using achievement L' formula by intelligent estimation method, the current density and ohmic losses on the cross section of the rail are computed. Ohmic losses are the source heat and utilized heat equation that are used to compute thermal distribution and temperature that are compared with other results in some papers. This paper chose $\mathrm{h} = 30$ mm, $\mathrm{w} = 10$ mm, and copper for the rail material and a method to compute the thermal distribution on the surface of the rail and side rail edges. Effects of rail dimensions on the temperature in time domain are calculated and shown in the figures. Rail materials are investigated with copper and aluminum in which the average temperature of both materials on the rail surface is calculated and compared.**

***Index Terms*—Intelligent estimation method with time variations (IEM-TD), maximum temperature, ohmic loss, railgun, thermal distribution.**

I. Introduction

THERMAL distribution and temperature value on the rails when passing high current through it are important factors to change the lifetime of a railgun. Ohmic losses are the source to produce the thermal and raise temperature in electrical systems that are computed by current density on solid structure.

Several studies have been reported on the thermal profile in railgun. M. Ghassemi calculated the temperature control and maximum temperature using energy and momentum equations in two papers [1], [2]. J. F. Kerrisk also considered the effect of rail dimension on temperature [3]. K. T. Hsieh used the Lagrangian formulation to compute the temperature for moving and stationary armatures [4].

The main objective of IEM technique is to obtain a closed formula for the quantity of output based on approximation of the answer for isolated parts of the structure as in [5]. In this paper, using L' formula expressed in [5], the current density on the surface of the rail and the ohmic losses have been calculated.

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TABLE I
MATERIAL PROPERTIES

Quantity	Copper	Aluminum
σ (1/Ω.m)	5.8×10^7/ (1+0.0039(T-300))	2.56×10^7/ (1+0.0039(T-300))
Cp (J/k.kg)	0.0987T+355	0.486T+766
ρ (kg/m^3)	8900	2700

T = Temperature (°k)

Using the heat equation in the discretization case of the rail cross section, thermal distribution is calculated on the surface and around the rail.

Using this technique, the effect of width and thickness of rails upon the temperature is calculated and compared with the results in [3]. According to Table I, rail materials are investigated with copper and aluminum in which the average temperature of both materials on the rail surface is calculated and compared.

For various rail grid (number of mesh), the summation of thermal density, maximum thermal density, and relative differential thermal density are computed and shown on the graphs. A simple structure of railgun with moving armature in the x-direction that consists of two parallel rails are shown in Fig. 1 in both views (front and side).

II. Problem Statement

IEM technique has been developed to calculate the current distribution. The complete report and various iterations of IEM-TD implementation are expressed in [6] that can be described by a summary of this technique. Based on this technique, first, the considered area is divided into several parts, then for each part, the differential equations are solved analytically, and appropriate answers are obtained.

This involves the consideration of all influential parameters such as physical dimensions, material, time-variation characteristics, thermal effect, and any other environmental conditions.

A. *Thermal Distribution*

The thermal equation is expressed as [4]

$$\nabla \cdot (k\nabla T) + S = C_p \frac{\partial T}{\partial t} \tag{1}$$

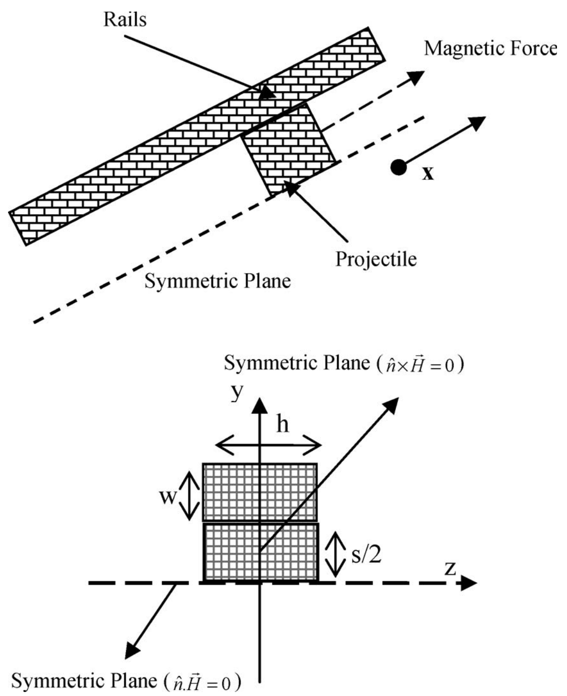

Fig. 1. Simple railgun.

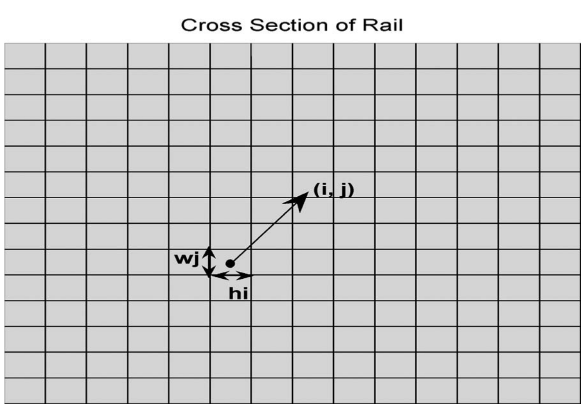

Fig. 2. Grid of rail cross section to compute the thermal distribution.

where k, C_p, and S are temperature-dependent thermal conductivity, temperature dependent specific heat, and heat source, respectively. To obtain the heat source, the following equation can be used:

$$S = \frac{\vec{J}\cdot\vec{J}}{\sigma(T)} \tag{2}$$

where **J** and $\sigma(T)$ are current density and temperature dependent electrical conductivity, respectively.

Meshing model of the cross section of the rail is shown in Fig. 2. This is divided by $(m \times n)$th element, in which the size of each element can be computed by equation

$$h_i = \frac{h}{m}, \quad w_j = \frac{w}{n} \tag{3}$$

where h_i and w_j are the thickness and width of the element, respectively. Passing current through each element, the current density can be obtained with the following equations:

$$I_{(i,j)} = \sqrt{2F_c/L'(h_i, w_j)} \tag{4}$$

$$J_{s(i,j)} = \frac{I_{i,j}}{(h_i \times w_j)} \tag{5}$$

where $L'(h_i, w_j)$, $I_{(i,j)}$, and $J_{s(i,j)}$ are inductance gradient, current, and current density over the surface for element (i, j), respectively. The inductance gradient formula is given by equation (6) as in [5]

$$L' = \frac{10^{-6}}{\frac{0.5986h}{s} + \frac{0.9683h}{s+2w} + \frac{4.3157}{\ln\left(\frac{4(s+w)}{w}\right)} - 0.7831}. \tag{6}$$

To compute the thermal distribution, we can combine equations (1), (2), and (5). Total thermal distribution over the rail cross section is obtained by the following equation:

$$T_s = \sum_{i=1}^{m}\sum_{j=1}^{m} T_{s(i,j)}. \tag{7}$$

The driving temperature around the rail is given by the following equations:

$$\begin{aligned}
T_{h1} &= \sum_{i=1}^{m}\left(T_{s(i,1)} - T_{s(i,2)}\right) w_j/h \\
T_{hn} &= \sum_{i=1}^{m}\left(T_{s(i,n-1)} - T_{s(i,n)}\right) w_j/h \\
T_{w1} &= \sum_{i=1}^{n}\left(T_{s(1,j)} - T_{s(2,j)}\right) h_i/w \\
T_{wm} &= \sum_{j=1}^{n}\left(T_{s(m-1,j)} - T_{s(m,j)}\right) h_i/w
\end{aligned} \tag{8}$$

where T_{h1}, T_{hn}, T_{w1}, and T_{wm} are temperatures on the line around the rail on the bottom, top, left, and right sides, respectively.

Rails are assumed to be made of copper, $w = s = 10$ mm and $h = 30$ mm. Fig. 3 shows the thermal distribution over the cross section of the rail given by equation (7). The thermal distribution on the rail circumference is shown in Fig. 4. According to these figures, thermal density is higher at the rails' inner edges. These phenomena can produce a hot point that fuses the rail edges and should be considered in railgun designing.

B. *Temperature Calculation and Comparison*

To calculate the temperature on the rail surface, data are used from material characteristics listed in Table I. The electrical conductivity and specific heat are dependent on temperature.

Fig. 5 shows the average temperature on the rail cross section for copper and aluminum rails. According to this figure, the average temperature in aluminum rail is higher than in copper rail. Fig. 6 shows the average temperature on the rail cross

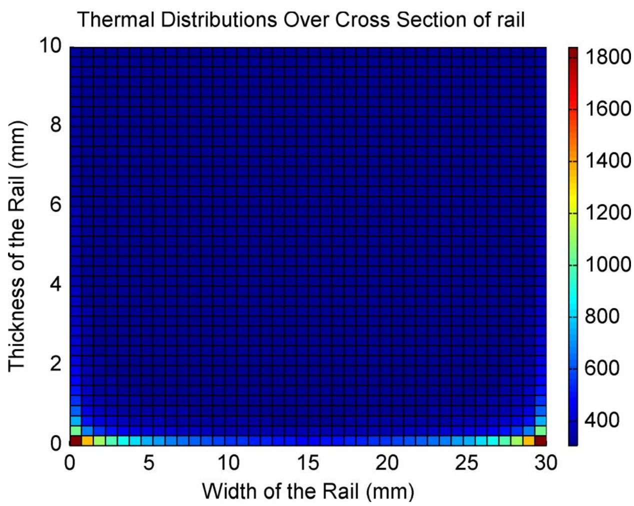

Fig. 3. Thermal distribution over the rail cross section.

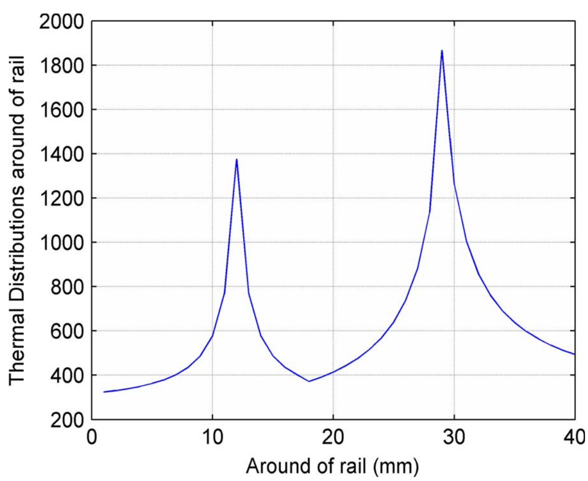

Fig. 4. Thermal distribution on the rail circumference.

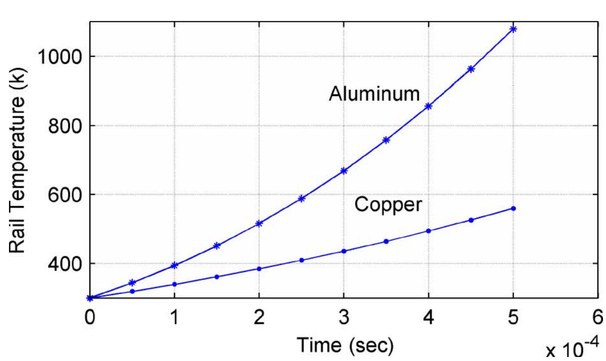

Fig. 5. Temperature average over the cross section of the rail as a function of time for various materials.

section for various dimensions that are compared with J. Kerrisk results as in [3]. Figs. 7 and 8 show a plot of high temperature in aluminum rail for stationary and moving armatures that are compared with results obtained as in [4].

III. Convergence of the IEM

In this section, for various numbers of mesh, the relative rrror, thermal summation, and maximum thermal density are

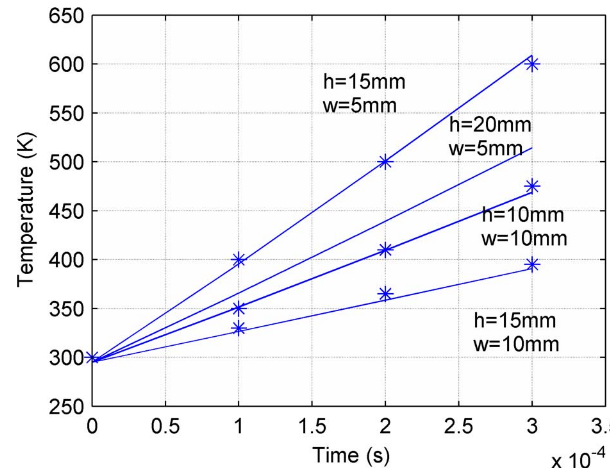

Fig. 6. Temperature average over the cross section of the rail as a function of time: results in [3] are marked by (– • –) and for this paper marked by (—).

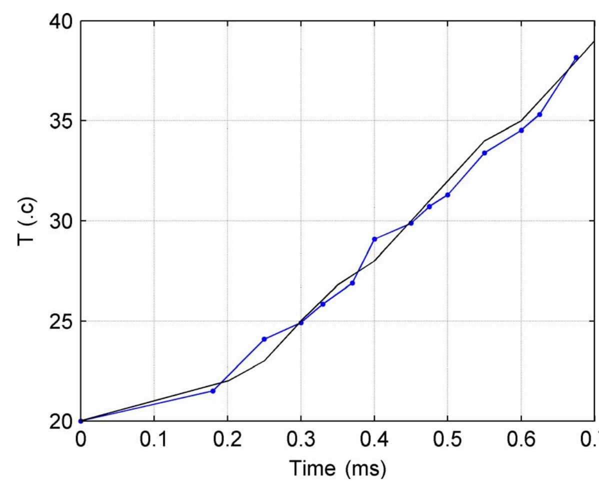

Fig. 7. High temperature in stationary model: results in this paper are marked by (– · –), and results in [4] are marked by (—).

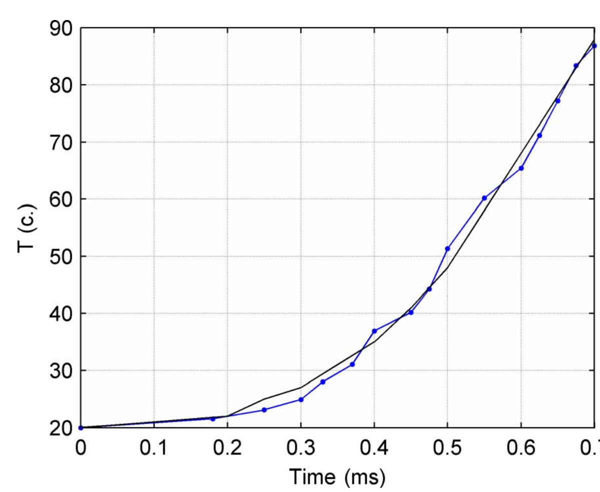

Fig. 8. High temperature in moving model: results in this paper are marked by (– · –), and results in [4] are marked by (—).

computed and shown in Figs. 9–11. According to these figures, the IEM technique results are independent on grid size or mesh numbering.

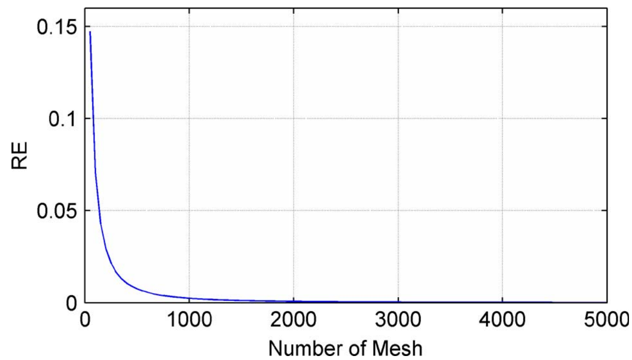

Fig. 9. Relative error for thermal density.

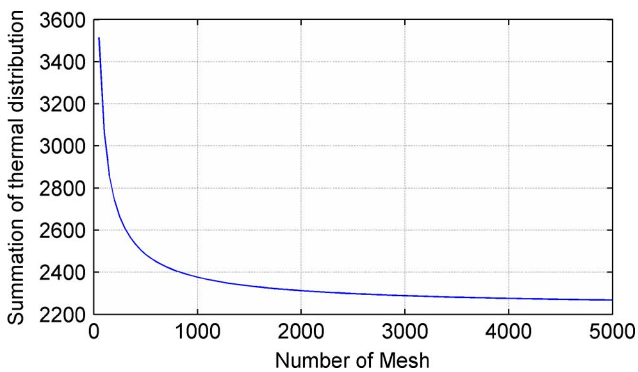

Fig. 10. Summation of thermal density on rail cross section.

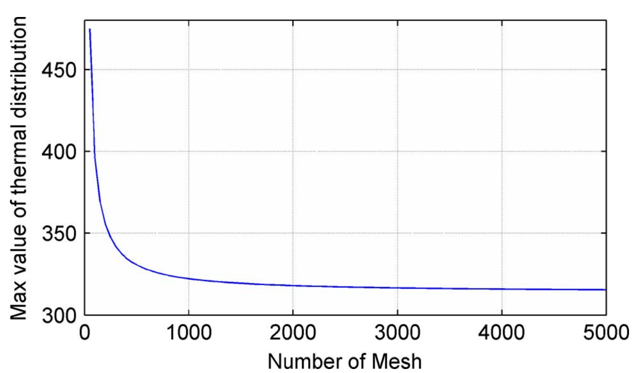

Fig. 11. Maximum value of thermal density on rail cross section.

IV. Conclusion

In this paper, a novel method is introduced to derive the thermal distribution. Intelligent estimation method with time variations (IEM-TD) is proposed that can be used to calculate the thermal distribution.

It should be noticed that the satisfactory advantage of utilizing IEM- TD is that it can be used to prepare an enormous ability to develop a simplified general governing formula to sufficiently describe any complicated structures analytically. In comparison with other published papers, our formulation satisfies their numerical results with slight differences. Calculation of temperature and thermal distribution could be used to solve the low mean lifetime problem of the rectangular railguns.

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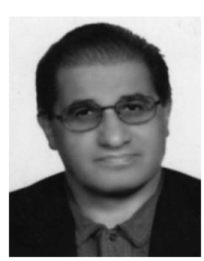

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