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Analysis of Crimped Connections Heat Transfer Coefficient Using Experimental and Numerical Determinations

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***Abstract* – In this paper is presented an analysis of the influence of heat transfer coefficient on temperature values using numerical and experimental results. The research was carried out on a crimped connection used at electrical generators manufacture. It was started by heating the crimped connection in AC regime at different electrical current intensities for obtaining the values of stabilised temperature. Then, the coefficient was calculated using two different methods. The first method, the analytical – experimental approach, consists in calculation of heat transfer coefficient values using a relation obtained starting from thermal regime equilibrium. The second method, calculation – experimental approach, involves using a minimize function which can be implemented in MathCad. After that, coefficient values were introduced in numerical simulation in order to determine temperature values. The numerical model was developed in QuickField software starting from a coupled problem AC Magnetics – Steady State Heat transfer. At the beginning the AC magnetic problem was solved with the objective of obtainig the heat source which was introduced in Steady State Heat Transfer problem. Finally, by using numerical and experimental results, errors were calculated with the aim of determining the efficience of these two methods. It was then concluded that, for domains which include electrical currents up to 1000 A, errors are relative small. But for high values of electrical currents another method for heat transfer coefficient should be developed.**

Cuvinte cheie: *coeficient de transfer termic, simulări numerice, probleme cuplate, determinări experimentale, conexiuni sertizate.*

Keywords: *heat transfer coefficient, numerical simulations, coupled problems, experimental determinations, crimped connections.*

I. INTRODUCTION

Lately, a lot of electrical equipments and machines failures are due to the inefficient usage of crimped connections. Due to their high efficiency at temperatures above soldering, crimped connections are more and more utilized in industry, especially in manufacture of electrical generators. Sometimes before final assembly of electrical machines there are necessary many electrical and mechanical tests involving this type of connection. These tests are time and energy consuming activities. So, a huge help could come from numerical simulations, of course not without the difficulty of choosing of the right numerical model, simulations parameters and conditions.

Several attempts were made having the main goal of finding the right model in order to simulate for example the thermal regime of crimped connections. In particular, in [2], [3], [5] were presented various methods for heat transfer coefficient determination which can be used in numerical simulations. Also, in the literature [4] are presented different values for this coefficient depending of material. In addition, there are some formulas that can help to calculate the value of heat transfer coefficient.

The main goal of this paper is to analyze the influence of heat transfer coefficient on temperature values using numerical and experimental results by calculating relative errors. The research was carried out on a crimped connection used at electrical generators manufacture having 8 copper wires 7.1 x 3 mm^2 crimped with one crimp indent (Fig. 1.).

Fig. 1. Crimped connection sample used for analyzes.

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II. HEAT TRANSFER COEFFICIENT DETERMINATION

A. *Analitical-experimental approach*

In order to determine heat transfer coefficient value, it can be assumed that at thermal equilibrium the heat quantity stored in the crimped connection is equal to heat transferred in the surrounded ambient and therefore, it can be written the equation:

$$R_{\mathrm{el}} \cdot I^2 = h_\Sigma \cdot (\theta_s - \theta_a) \cdot A \,. \tag{1}$$

where:

- R_{el} is electrical resistance;
- I is electrical current intensity;
- θ_s represents stabilized temperature;
- θ_a is ambient temperature;
- A is considered the area of heat transfer.

Taking into account the dependence between electrical resistance and resistivity, the relation corresponding to the global coefficient of heat transfer h_Σ can be written as follow:

$$h_\Sigma = \frac{k_p \cdot \rho_{20} \cdot \left[1 + \alpha_R \cdot (\theta_s - 20)\right] \cdot I^2}{A \cdot (\theta_s - \theta_a) \cdot l_p} \,. \tag{2}$$

Where:

- k_p is considered a coefficient that takes into account the skin effect;
- ρ_{20} is noted electrical resistivity at 20 ˚C;
- α_R is resistance variation coefficient with temperature.

Using (2) and experimental values of temperature corresponding to the crimped connection, heat transfer coefficient can be obtained. Results are presented in table I.

TABLE I
HEAT TRANSFER COEFFICIENT VALUES : ANALITICAL-EXPERIMENTAL APPROACH

I [A]	510	682	855	1110
θ_{exp} [˚C]	62.3	94.5	132.9	212.4
h_Σ [Wm^{-2}K^{-1}]	1.65	1.78	2.13	2.53

B. *Calculation - experimental approach*

Starting from experimental results (Table I) and using a minimize procedure in MathCad [3], it can be obtain an initial law for minimize function:

$$F(\Delta\theta, k_1, k_2, k_3) = k_3 + k_1 \cdot (\Delta\theta)^{k_2} \,. \tag{3}$$

Sum of squares to be minimized can be written as follow:

$$SSE(k_1, k_2, k_3) = \sum_{i=1}^{4} \left(h_i - F(\Delta\theta_i, k_1, k_2, k_3)\right)^2 \,. \tag{4}$$

Final parameters resulted from using minimize function are:

- $k_1 = 0.065$
- $k_2 = 0.6$
- $k_3 = 1.01$

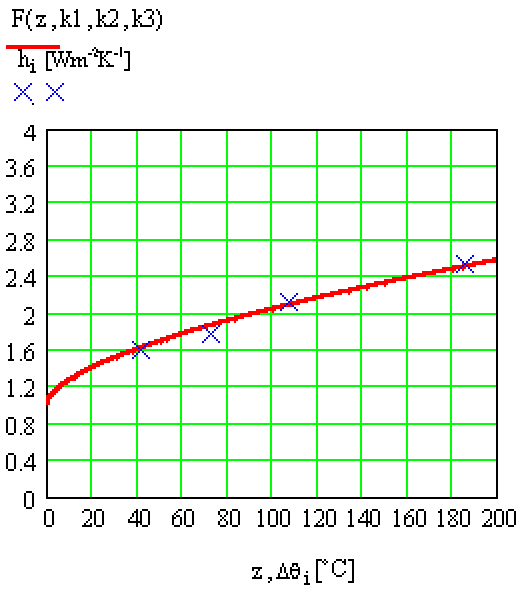

Fig. 2. Heat transfer coefficient variation resulted from minimization.

Thus, it can be written the final law for heat transfer coefficient:

$$h_\Sigma(\Delta\theta) = 1.01 + 0.065 \cdot (\Delta\theta)^{0.6} \,. \tag{5}$$

Using (5) heat transfer coefficient can be calculated for different temperature values and the results are presented in table II.

TABLE II
HEAT TRANSFER COEFFICIENT VALUES : CALCULATION-EXPERIMENTAL APPROACH

I [A]	510	682	855	1110
θ_{exp} [˚C]	62.3	94.5	132.9	212.4
h_Σ[Wm^{-2}K^{-1}]	1.61	1.86	2.08	2.5

III. NUMERICAL VERIFICATION OF HEAT TRANSFER COEFFICIENT VALUES

A. *Numerical model*

Numerical simulations are based on a coupled AC Magnetics – Steady-State Heat Transfer problem having a model with two components [2], magnetic model and thermal model, which are coupled through the source term (specific Joule heat):

$$S(\theta) = \rho(\theta) \cdot J^2(x, y) \,. \tag{6}$$

The equation that governs the magnetic model is:

$$\left(\frac{1}{\mu} \cdot \frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y} \cdot \left(\frac{1}{\mu} \cdot \frac{\partial A}{\partial y}\right) - - j \cdot \omega \cdot \sigma(\theta) \cdot A = -J_s \,. \tag{7}$$

Similarly, for the thermal model the equation can be written as:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\theta}{\partial y}\right)+S(\theta)=0\,. \qquad (8)$$

where:

- σ - electric conductivity;
- μ - magnetic permeability;
- A - magnetic potential vector;
- J - current density source;
- ρ – resistivity;
- θ – temperature;
- λ – thermal conductivity;
- S- source term.

In order to obtain numerical results, a 2D planar model was created in QuickField Professional and a coupled problem AC Magnetics – Steady-State Heat Transfer was solved.

Fig. 3 shows the analysis domain and Fig. 4 the boundary conditions.

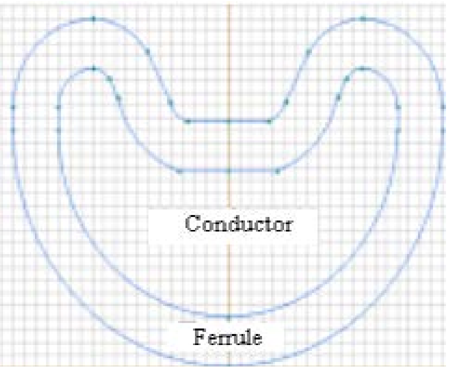

Fig. 3. Analysis domain of crimped connection in QuickField.

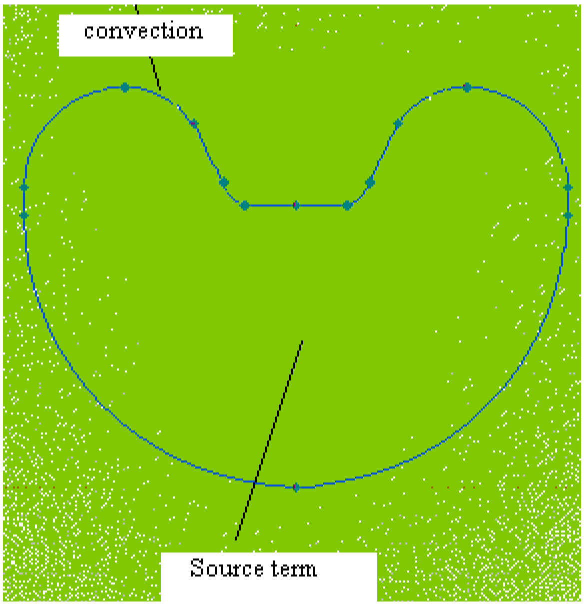

Fig. 4 Boundary conditions for thermal model.

B. Numerical results

Numerical simulations were made considering the same values for electrical current intensity as in experimental determinations 510 A, 682 A, 855 A and 1110 A, until the steady state regime was achieved.

In the first part of the simulations the AC Magnetics problem was solved in order to obtain the specific Joule heat, which was considered the source term. Then it was imported in steady state heat transfer problem which was coupled with AC magnetic problem. By doing this, the problem will give the right results according to initial values defined in the model.

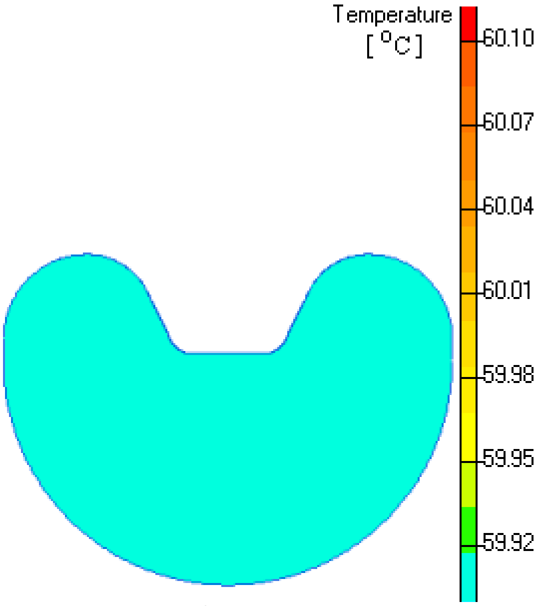

Fig. 5 . Temperature values for the case analitical-experimental approach., I = 510 A, h_{Σ} = 1.65 [$Wm^{-2}K^{-1}$]

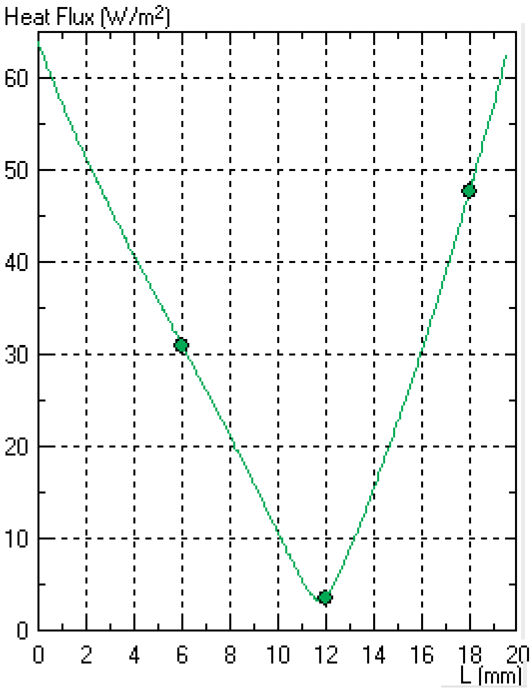

Fig. 6 . Heat flux values for the case analitical-experimental approach., I = 510 A, h_{Σ} = 1.65 [$Wm^{-2}K^{-1}$]

Temperature values and heat flux corresponding to different electrical current values considering the case of analitical-experimental approach are presented in Fig. 5 - 9. In this case the values for h_Σ (Table I) were utilised.

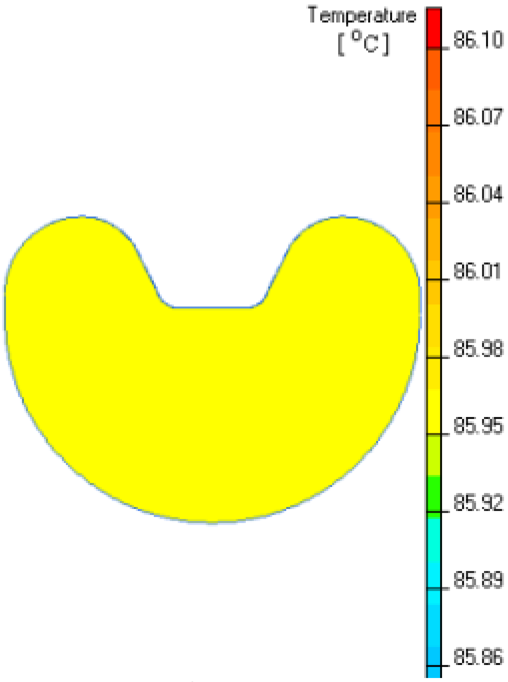

Fig. 7 . Temperature values for the case analitical-experimental approach., I = 682 A, h_Σ = 1.78 [$Wm^{-2}K^{-1}$]

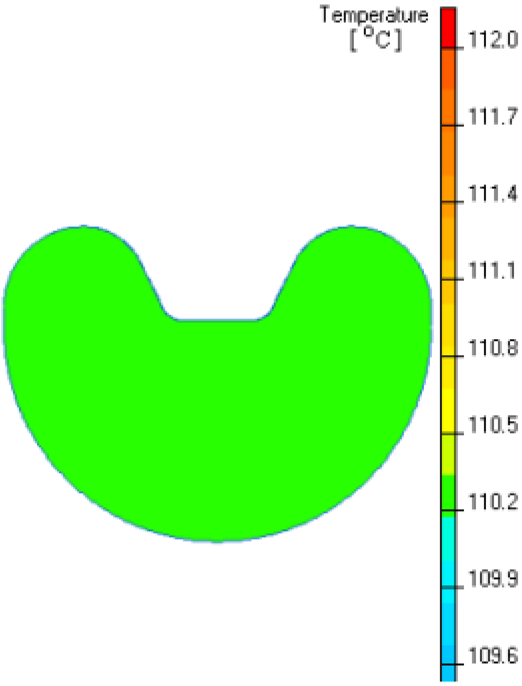

Fig. 8 . Temperature values for the case analitical-experimental approach., I = 855 A, h_Σ = 2.13 [$Wm^{-2}K^{-1}$]

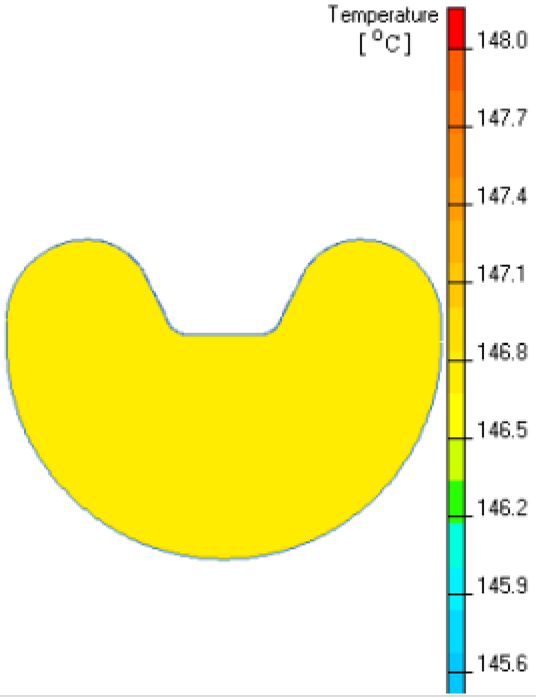

Fig. 9 . Temperature values for the case analitical-experimental approach., I = 1110 A, h_Σ = 2.53 [$Wm^{-2}K^{-1}$]

Following the same line, the temperatures in the case of calculation – experimental approach, using the values for heat transfer coefficient from Table II, are illustrated in Fig. 10 – 13.

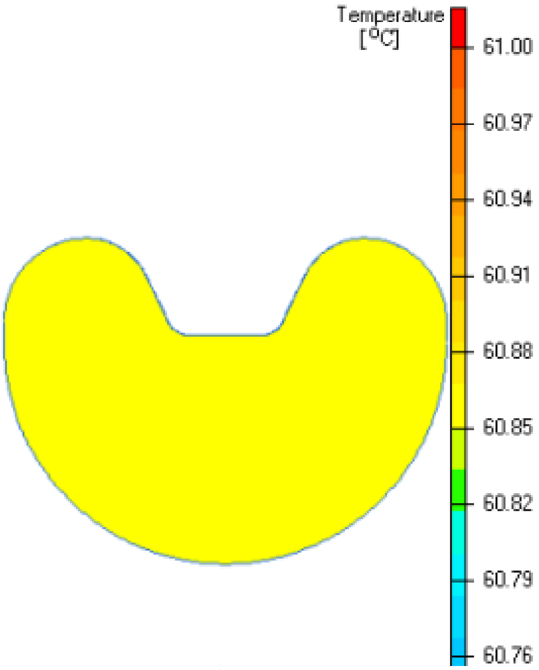

Fig. 10 . Temperature values for the case calculation - experimental approach., I = 510 A, h_Σ = 1.61 [$Wm^{-2}K^{-1}$]

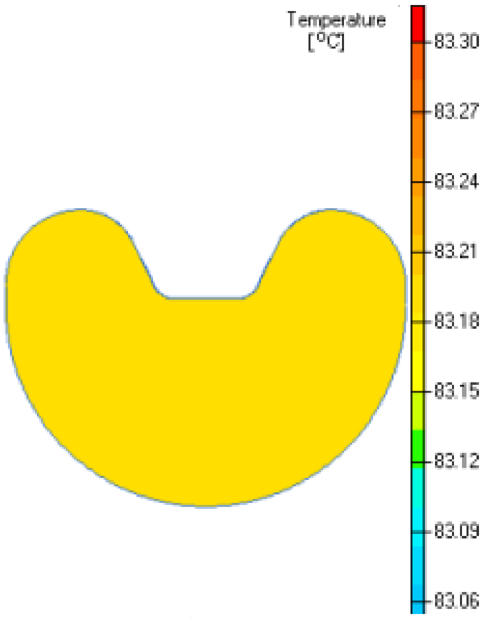

Fig. 11 . Temperature values for the case calculation - experimental approach., I = 682 A, h_{Σ} = 1.86 [Wm^{-2}K^{-1}]

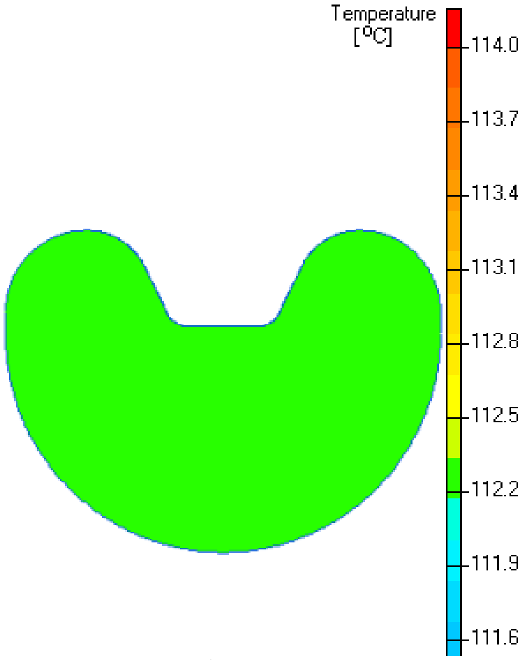

Fig. 12 . Temperature values for the case calculation - experimental approach., I = 855 A, h_{Σ} = 2.08 [Wm^{-2}K^{-1}]

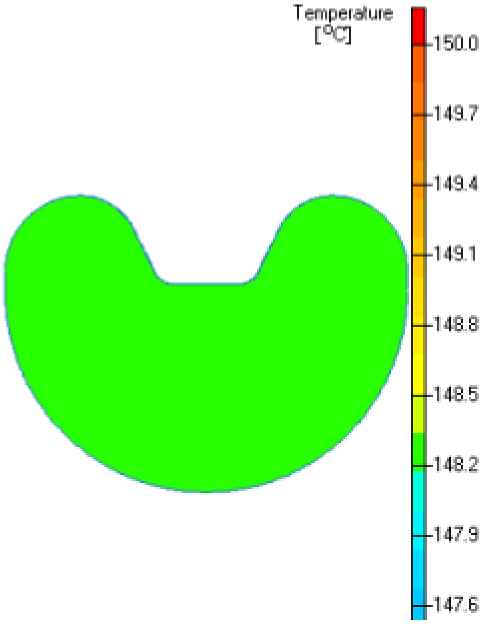

Fig. 13 . Temperature values for the case calculation - experimental approach., I =1110 A, h_{Σ} = 2.5 [Wm^{-2}K^{-1}]

C. *Results analysis*

Starting from temperature values resulted from numerical and experimental determinations, errors had been calculated and their values are presented in Table III, Table IV. In order to calculate errors, numerical temperature values resulted from using heat transfer coefficient in both cases, analytical - experimental approach and calculation – experimental approach, and experimental values were compared.

TABLE III
ERRORS VALUES – COMPARISON BETWEEN ANALYTICAL – EXPERIMENTAL APPROACH AND EXPERIMENTAL DETERMINATION

I [A]	510	682	855	1110
θ_{exp} [˚C]	62.3	94.5	132.9	212.4
θ_{numI} [˚C]	59.9	85.9	110.2	146.7
Error [%]	3.85	9.1	17	31

TABLE IV
ERRORS VALUES – COMPARISON BETWEEN CALCULATION – EXPERIMENTAL APPROACH AND EXPERIMENTAL DETERMINATION

I [A]	510	682	855	1110
θ_{exp} [˚C]	62.3	94.5	132.9	212.4
θ_{numII} [˚C]	60.8	83.2	112.3	148.2
Error [%]	2.4	11.9	15.5	30.2

In Table III and Table IV were used next notations:

- θ_{numI} - numerical value of temperature for the case analytical - experimental approach
- θ_{numII} - numerical value of temperature for the case calculation - experimental approach
- θ_{exp} – experimental value of temperature

IV. CONCLUSIONS

In numerical simulations an extremely important parameter is heat transfer coefficient. Its values have a significant influence on temperature final results. Thus, in order to investigate which method is the most reliable to calculate this coefficient with minimum errors, it was started from an analytical formula and a method which use a minimize procedure. Then, the numerical results for temperature were compared with experimental results.

It can be observed that in the case of *Calculation – experimental approach* the errors are slightly smaller than in the case of *Analytical – experimental approach*. But, both cases are given large errors for big values of electrical currents, for example in the case of electrial currents bigger than 1000 A (30 % or 31 % irrespective).

In conclusion, it can be argued that for high currents domain another methods should be used for heat coefficient values determination, while for small currents values one of the two presented methods can be used with small errors.

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First coauthor – 25%

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