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CALCULATION OF THE HEAT TRANSFER IN CYLINDRICAL WIRES AND ELECTRICAL FUSES BY IMPLICIT FINITE VOLUME METHOD

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ABSTRACT

The usual wire rating problem is to compute the permissible conductor current so, that the maximum conductor temperature does not exceed a specified value. When numerical methods are used to determine wire rating, an iterative approach has to be used for this purpose. This is accomplished by specifying a certain conductor current and computing the corresponding conductor temperature. The electrical fuse rating problem is to calculate the melting behavior and to match thermo-electrical characteristic of the wire and fuse in a way that the wire is protected by a fuse in wanted time and current range.
Up to now the selection of wires is based on data, which were not particular optimized for automotive applications, where the wire length is typically short and low weight is important. The same, electrical fuses today are designed for a certain current value and do not protect the wire reliable in a wider current range. So, for automobile applications, fuses have to be re-designed for every single wire to protect it against short circuit currents. Thus, the investigation of thermo-electrical characteristics of both wires and fuses is necessary.
This paper would like to show some examples how to calculate heat transfer in cylindrical wires (cable rating) and electrical fuses (melting behavior) by implicit Finite Volume Method (FVM) [12]. Such a procedure allows us to obtain simple algorithm to investigate thermo-electrical behavior of electrical conductors.
The key part of the paper is the calculation of the heat transfer by implicit Finite Volume Method. In non-stationary state 1-D heat conduction equation is solved for both cylindrical and orthogonal coordinates. In stationary state analytical solutions are presented.

Key words: heat transfer, natural convection, radiation, cylindrical wire, electrical fuse, mathematical modeling, implicit finite volume method, implicit Euler algorithm, Newton-Raphson method

1. INTRODUCTION

Thermal analysis of cylindrical wires and cables is a topic that received considerable attention by many researchers [3; 5; 7]. Using different solution methods researchers have thoroughly analyzed heat transfer by natural convection around a vertical and horizontal cylinder [6]. As mentioned recently by Haskew [3] non-linear boundary conditions almost exclusively were linearized using Gauss-Seidel method [2], which offers linear convergence. Such a choice requires a large number of iterations on an equally large system of equations. Herein, a finite volume heat transfer model is employed, where non-linear boundary conditions resulting from convection and radiation are treated by the Newton-Raphson technique [2].

A finite volume solution grid is imposed on the wire cross section or fuse axial length and a single power balance equation is written about each control volume. The heat balance equations at interior nodes are linear in temperature, while power balance equations at boundary nodes are non-linear as a result of the non-linear convection and radiation equations. This formulation, along with the inclusion of boundary conduction and convection, has been employed by other researchers in the field and presented in the literature [5]. The other authors have implemented finite-element solutions to the same equation applied to underground geometry systems [10; 11]. However, in these systems non-linear boundary conditions were not imposed. For the problem considered here, boundary radiation is treated.

While constructing numerical grid of the electrical wire, interior nodes lies in conducting and insulating media. Only nodes within conducting medium are considered for internal heat generation, which is a linear function of conductor resistance. Conductor resistance is treated as a linear function of temperature over the reasonable operating range. Such consideration of resistance variation allows highly accurate ampacity computations. Previous work has treated resistance variations in an outer iterative loop analogous to fixed-point iteration [4] or utilized a maximum resistance value [9].

System of algebraic equations is constructed using the implicit Euler algorithm [2], which means that equations have to be solved simultaneously at one time level. The implicit algorithm versus explicit numerical algorithm brings to proposed numerical scheme unconditional stability and computational efficiency.

2. THE MATHEMATICAL MODEL

We shall consider two different heat transfer problems. The first problem deals with axial heat transfer calculation in a bras hollow cylinder (fuse prototype) with finite length. The governing equation is the following:

$$\frac{\partial}{\partial x}\Big(\lambda\frac{\partial\Delta T}{\partial x}\Big) - \frac{\alpha(\Delta T,d)u\Delta T}{A} + p(\Delta T) - \gamma\frac{\partial\Delta T}{\partial t} = 0. \qquad (2.1)$$

The second task is the determination of temperature distribution in the radial direction of a round insulated electrical wire. The governing equation is the following:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(r)\cdot r\frac{\partial \Delta T}{\partial r}\right)+p(\Delta T,r)-\gamma(\Delta T)\frac{\partial \Delta T}{\partial t}=0, \tag{2.2}$$

where ΔT is the difference between temperature T and environment temperature $T_{env}(K)$, λ is the coefficient of heat conductivity (W/mK), α is a convective heat transfer coefficient (W/m^2K) [1], $p = E(T)J$ is the thermal source (W/m^3), where E – electrical field strength (V/m), $J = I/A$ – current density, where I is electrical current (A) and A is area of conductor (m^2), u is circumference of the cylinder (m), γ is a specific heat capacity (J/kgK).

For cylindrical coordinates (cylindrical wire), we have two-layer media, i.e. metallic conductor and insulation. In general, electrical cable can have multilayer media, therefore media Ω consists of N layers:

$$\Omega=\left\{r : r\in\bigcup_{i=1}^{N}\Omega_i\right\},\quad \Omega_i=\{r : r_{i-1}\le r\le r_i\}\quad i=1,2,\ldots,N,$$

and $r = r_i,\ k=\overline{1,N}$ are the boundaries of the layers.

The following conditions are applied:

1. The continuity conditions on the surfaces $r = r_i$:

$$\begin{cases}\Delta T_i(r_i,t)=\Delta T_{i+1}(r_i,t),\\ -\lambda_i r_i\dfrac{\partial \Delta T_i(r_i,t}{\partial r})\Big|_{r=r_i}=-\lambda_{i+1}r_i\dfrac{\partial \Delta T_{i+1}(r_i,t}{\partial r})\Big|_{r=r_i};\end{cases} \tag{2.3}$$

2. The initial conditions

$$\Delta T(x,0)=\Delta T_0(x),\quad x\in[0,x_N], \tag{2.4}$$
$$\Delta T(r,0)=\Delta T_0(r),\quad r\in[0.5,r_N]; \tag{2.5}$$

3. The boundary conditions on the surfaces $x = x_0$ and $x = x_N$:

$$\begin{cases}\Delta T(0,t)=\Delta T_1(t),\\ \Delta T(r,0)=\Delta T_N(t),\end{cases} \tag{2.6}$$

the boundary conditions on the surfaces $r = r_0$ and $r = r_N$

$$\begin{cases}\lim\limits_{r\to 0} r\lambda_1\dfrac{\partial \Delta T_1(r_0,t)}{\partial r}=0,\\ -r\lambda_N\dfrac{\partial \Delta T}{\partial r}\Big|_{r=r_N}=\alpha(d,\Delta T)(T_N(r_N,t)-T_{env})\\ \qquad\qquad\qquad +\varepsilon\sigma(T_N^4(r_N,t)-T_{env}^4),\end{cases} \tag{2.7}$$

where d is a diameter of conductor $(m), T_N$ is the temperature of wire surface $(°C)$, T_{env} is environment temperature $(°C), \varepsilon$ is emissivity coefficient and σ is Stefan-Boltzmann constant, $\sigma = 5,67\,10^{-8}\,(W/m^2K^4)$.

3. ANALYTICAL SOLUTION FOR STEADY STATE REGIME

Equations (2.1) and (2.2) in steady state case takes the following form:

$$\frac{d}{dx}\Big(\lambda\frac{dT}{dx}\Big) - \frac{\alpha u T}{A} + p = 0, \tag{3.1}$$

$$\frac{1}{r}\frac{d}{dr}\Big(\lambda r\frac{dT}{dr}\Big) + p = 0. \tag{3.2}$$

In order to obtain analytical solutions we apply the following assumptions:

- convection coefficient α is temperature independent;
- thermal source p is temperature independent;
- no temperature gradient in the metallic conductor (see Fig.1)

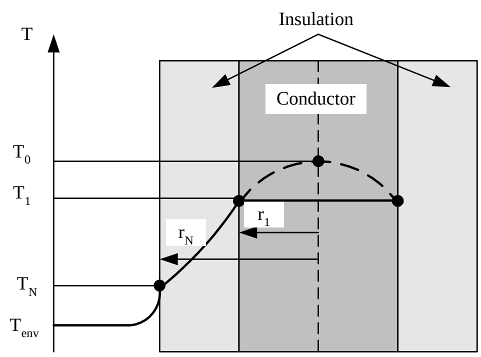

Figure 1. Temperature profile in the metallic wire and its insulation. Here T_0 is temperature in the axis of the wire, T_1 is temperature at the interface between wire and insulation (an assumption was made, that the temperature at the surface of the wire is equal to the temperature at the inner side of the insulation), T_N is the temperature on the outer side if the insulation and T_{env} is temperature of environment.

The solution of Eq. (3.1) is given by

$$T(x) = T_1 \exp\Big(\sqrt{\frac{\alpha u}{\lambda A}}x\Big) + T_2 \exp\Big(\sqrt{\frac{\alpha u}{\lambda A}}x\Big)\frac{p}{\lambda}. \tag{3.3}$$

Taking into account boundary conditions (2.6) we get:

$$T(x) = \frac{\left(T_1 - \frac{p}{\lambda}\right)\left(1 - \exp\left(-\sqrt{\frac{\alpha u}{\lambda A}} x_N\right)\right)\exp\left(\sqrt{\frac{\alpha u}{\lambda A}}(x - x_N)\right)}{1 - \exp(-2\sqrt{\frac{\alpha u}{\lambda A}} x_N)} + \frac{\left(T_1 - \frac{p}{\lambda}\right)\left(1 - \exp\left(-\sqrt{\frac{\alpha u}{\lambda A}} x_N\right)\right)\exp\left(-\sqrt{\frac{\alpha u}{\lambda A}} x\right)}{1 - \exp(-2\sqrt{\frac{\alpha u}{\lambda A}} x_N)} + \frac{p}{\lambda}. \tag{3.4}$$

In order to obtain the solution of the Eq. (3.2) we reconsider the boundary conditions. As a first limit condition we do not consider the symmetry boundary condition (as for numerical approach) but the joint between metallic conductor and insulation layer. The second limit condition remains the same as for numerical approach but without non-linear heat radiation to the surface part:

$$\begin{cases} \left.\frac{dT}{dr}\right|_{r=r_1} = -\frac{EI}{2\pi r_1 \lambda_1}, \\ \left.\frac{dT}{dr}\right|_{r=r_N} = \frac{\alpha}{\lambda_N}(T_N - T_{env}). \end{cases} \tag{3.5}$$

For $r_1 < r < r_N$ Eq. (3.2) can be written as follows:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) = 0, \tag{3.6}$$

which after integration becomes equal to

$$\frac{dT}{dr} = \frac{c}{r}, \tag{3.7}$$

where c is an integration constant. Taking into account the limit condition (3.5) the constant c is given by:

$$c = -\frac{EI}{2\pi\lambda_N}. \tag{3.8}$$

According to the second limit condition (3.5), the temperature of the outer surface of the insulation is:

$$T_i = T_{env} + \frac{EI}{2\pi r_N \alpha}. \tag{3.9}$$

The temperature profile in the insulation ($r_1 \leq r \leq r_N$) can be determined by integrating the equation (3.7):

$$T(r) = T_1 + \frac{EI}{2\pi\lambda_N} \ln \frac{r_N}{r_1}. \tag{3.10}$$

Finally, the temperature at $r = r_1$ is expressed as:

$$T_1 = T_{env} + \frac{pA}{2\pi r_N \alpha} + \frac{pA}{2\pi\lambda_N} \ln \frac{r_N}{r_1}. \tag{3.11}$$

4. THE IMPLICIT FINITE VOLUME METHOD

Using the implicit finite volume method [2], we obtain the finite volume scheme approximated by central differences. In time, differential equations (2.1) and (2.2) are approximated using the *implicit* Euler method. The approximation by FVM can be obtained in the following steps:

1. Equations (2.1) and (2.2) should be re-written in the integral form. We integrate the equation over a small fixed volume $\boldsymbol{V}$.
2. The volume integral over the heat flux vector is transformed to a surface integral by means of the divergence theorem.
3. We apply the integration form to the finite volume $V_i = [i - 0.5; i + 0.5]$.
4. The integral form over finite volume $V_i = [i - 0.5; i + 0.5]$ is replaced by central differences in space and backward differences in time.

Then the discrete forms are given as follows:

a) for cylindrical tube (fuse), axial heat transfer:

$$\begin{cases} \Delta T_1^n = T_{env}, \quad i = 1, \\ -\dfrac{\lambda_{i+1/2}}{\Delta x_{i+1/2}} \left(\Delta T_{i+1}^n - \Delta T_i^0 \right) + \dfrac{\lambda_{i-1/2}}{\Delta x_{i-1/2}} \left(\Delta T_i^n - \Delta T_{i-1}^0 \right) \\ \quad + \dfrac{\alpha u}{A} \Delta T_i^n \Delta x_i + \dfrac{\gamma_i^n \Delta x_i}{\Delta t} \left(\Delta T_i^n - \Delta T_i^{n-1} \right) = p_i \Delta x_i, \\ \qquad 1 < i < N, \\ \Delta T_N^n = T_{env}, \quad i = N, \end{cases} \tag{4.1}$$

b) for cylindrical wire, radial heat transfer:

$$\begin{cases} -\dfrac{r_{1/2}\lambda_{0.5}}{\Delta r_{1/2}}\left(\Delta T_1^n - \Delta T_0^n\right) + \dfrac{\Delta r_0 r_{1/2}\gamma_{0.5}^n}{\Delta t}\left(\Delta T_0^n - \Delta T_0^{n-1}\right) \\ \qquad\qquad\qquad\qquad = \Delta r_0 r_{1/2} p_0, \quad i = 0, \\ -\dfrac{r_{i+1/2}\lambda_{i+1/2}}{\Delta r_{i+1/2}}\left(\Delta T_{i+1}^n - \Delta T_i^n\right) + \dfrac{r_i r_{i-1/2}\lambda_{i-1/2}}{\Delta r_{i-1/2}}\left(\Delta T_i^n - \Delta T_{i-1}^n\right) \\ \quad +\dfrac{\Delta r_i \gamma_i^n}{\Delta t}\left(\Delta T_i^n - \Delta T_i^{n-1}\right) = \Delta r_i r_1 p_i, \quad 1 < i < N, \\ \alpha(T_N^n - T_{env}) + \varepsilon\sigma\Big((T_N^n)^4 - T_{env}^4\Big) + \dfrac{r_{N-1/2}\lambda_{N-1/2}}{\Delta r_{N-1/2}}\left(T_N^n - T_{N-i}^n\right) \\ \quad +\dfrac{\gamma_i^n(T) r_N \Delta r_N}{2\Delta t}\left(\Delta T_N^n - \Delta T_N^{n-1}\right) = \dfrac{1}{2} r_N \Delta r_N p_N^n, \quad i = N. \end{cases} \tag{4.2}$$

5. NEWTON-RAPHSON METHOD FOR SOLVING THE SYSTEM OF ALGEBRAIC EQUATIONS

Since, we have to deal with one-dimensional heat transfer problem Eq. (4.1), the Gauss elimination method [8] can be further simplified by taking advantage of the zeros of the tridiagonal coefficient matrix. This modified procedure, generally referred to as *Thomas Algorithm* [2], is an extremely efficient method for solving large number of such equations. Using this algorithm, the number of basic arithmetic operations for solving a tridiagonal set is of the order N, in contrast to $O(N^3)$ operations required for solving with Gauss Elimination. Therefore, not only are the computation times much shorter, but the round off errors also are significantly reduced.

The Newton-Raphson iteration method [8] is used to linearise equations (4.2). The Newton-Raphson method is an algorithm for finding the roots of systems of nonlinear algebraic equations by iteration. If a good initial guess is made, Newton-Raphson iteration process converges extremely fast. Iterations are terminated when the computed changes in the values of p^n become less than some specified quantity ε.

Applying Thomas Algorithm Eq. (4.1) is turned into the form:

$$\begin{cases} c_0\Delta T_0^n - b_0\Delta T_1^n = p_0^n; \\ -a_1\Delta T_0^n + c_1\Delta T_1^n - b_1\Delta T_2^n = p_1^n; \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ -a_j\Delta T_{j-1}^n + c_j\Delta T_j^n - b_j\Delta T_{j+1}^n = p_j^n \quad j = 1,\ldots,N-1; \\ -a_N\Delta T_{N-1}^n + c_N\Delta T_N^n = p_N^n. \end{cases} \tag{5.1}$$

Temperature variables ΔT are found by the following relationships:

$$\begin{cases} \alpha_0 = \dfrac{b_0}{c_0};\ \beta_0 = \dfrac{p_0}{c_0}; \\ \alpha_j = \dfrac{b_j}{c_j - a_j\alpha_{j-1}}; \beta_j = \dfrac{p_j + a_j\beta_{j-1}}{c_j - a_j\alpha_{j-1}}; \\ T_N^n = \dfrac{p_N + a_N\beta_{N-1}}{c_N - a_N\alpha_{N-1}} \quad T_i^n = \alpha_i T_{i+1}^n + \beta_i,\ i = 1,\dots,N-1; \end{cases} \tag{5.2}$$

where:

$$\begin{aligned} &a_j = \frac{\lambda}{\Delta x^2},\ b_j = \frac{\lambda}{\Delta x^2},\ c_j = \frac{2\lambda}{\Delta x^2} + \frac{\gamma}{\Delta t} + \frac{\alpha u}{A}, \\ &p_j = EJ + \gamma_i \frac{T_i^{n-1}}{\Delta t}, \quad j = 1,2,\dots,N-1; \\ &a_N = \frac{1}{\Delta x^2},\ c_N = \frac{1}{\Delta x^2} + \frac{\gamma}{\Delta t} + \frac{\alpha u}{A},\ p_N = EJ + \gamma_N \frac{T_N^{n-1}}{\Delta t},\ j = N. \end{aligned}$$

After applying the Newton-Raphson method, nonlinear system of equations (4.2) turns into:

$$\begin{cases} c_0 P_0^n - b_0 P_1^n = p_0^n - c_0\Delta T_0^n + b_0\Delta T_1^n; \\ -a_1 P_0^n + c_1 P_1^n - b_1 P_2^n = p_1^n + a_1\Delta T_0^n - c_1\Delta T_1^n + b_1\Delta T_2^0; \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ -a_j P_{j-1}^n + c_j P_j^n - b_j P_{j+1}^n = p_j^n + a_j\Delta T_{j-1}^n - c_j\Delta T_j^n \\ \quad +b_j\Delta T_{j+1}^0; \qquad j = 1,\dots,N-1; \\ -a_N P_{N-1}^n + (c_N + \alpha\lambda + \beta\lambda 4(T_N^n)^3)P_N^n = p_N^n + \Delta T_N^{n-1} \\ \quad +a_N\Delta T_{N-1}^n + (-c_N - \alpha\lambda)T_N^n - \beta\lambda(T_N^n)^4 - \alpha\lambda T_{env} - \beta\lambda T_{env}^4, \end{cases} \tag{5.3}$$

where P are unknown temperature variables, ΔT are initially guessed values.

Coefficients a, b, c of the system of linear equations (5.3) are calculated by:

$$\begin{aligned} &a_j = \frac{r\lambda}{\Delta x^2},\ b_j = \frac{r\lambda}{\Delta x^2},\ c_j = \frac{2r\lambda}{\Delta x^2} + \frac{\gamma}{\Delta t},\ p_j = EJ + \gamma_i \frac{T_i^{n-1}}{\Delta t}, \\ &\qquad j = 1,2,\dots,N-1; \\ &a_N = \frac{1}{\Delta x^2},\ c_N = \frac{1}{\Delta x^2} + \frac{\gamma}{\Delta t},\ p_N = EJ + \gamma_N \frac{T_N^{n-1}}{\Delta t},\ j = N. \end{aligned}$$

6. NUMERICAL RESULTS AND DISCUSSION

We have used the following data to calculate thermal behaviour in the fuse system with the blow-up element in the middle, made of Brass 58 (CuZn39Pb3) (see Fig.2): $N = 1$ (one layer was used: brass); $I = 180\,A$ is the current passing through the fuse; $\gamma = 410\,J/m^3\,K$ is the specific heat capacity; $\lambda = 113\,W/mK$ is the heat conductivity of brass; $T_{env} = 65°C$ is the temperature of the electrical wire.

To simulate heat transfer in cylindrical electrical wire the following data was used:

Type of the wire - FLY; cross-section – $16\,m^m2$; *max.* allowed temperature of the insulation – $90°C$; ($N = 2$) (two layers were used: copper and PVC insulation); I_1 = from 0 to 300 A; I_2= 0; $\lambda_1 = 401\,W/mK$, $\lambda_2 = 0.17\,W/mK$; γ_1, γ_2 are nonlinear specific heat capacity coefficients depending on temperature; $T_{env} = 65°C$ is the temperature of environment.

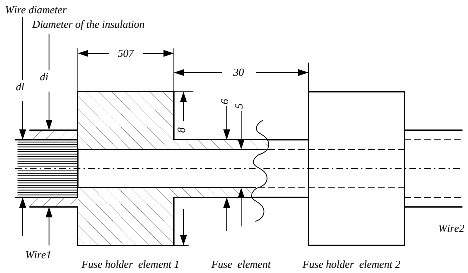

Figure 2. The conception of the Pyrofuse (hollow cylinder).

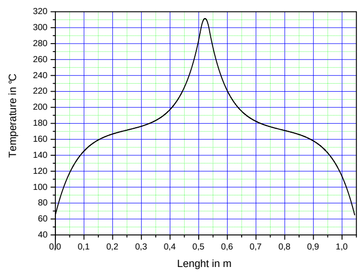

Figure 3. Temperature profile in the fuse element.

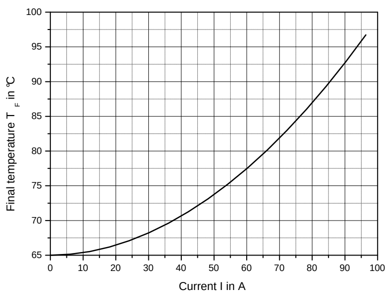

Figure 4. The function obtained from the numerical calculation of temperature (after steady state) in the metallic conductor of the wire for different current values.

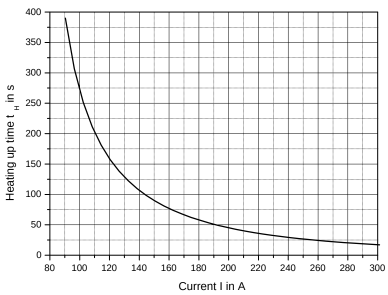

Figure 5. The function obtained from numerical calculation, where "heating – up time" was calculated, which determines maximum time can be handled by the wire applying the current represent in the picture. Here the limit condition for the heating-up time was 90^0C degrees.

In Fig.3 we presente fuse melting behavior with simplified fuse element geometry for better illustration purpose. From the picture can be seen the maximum temperature (310 °C) of the element after infinite time. This temperature was given by the fuse manufacturer and the aim was to choose the correct fuse element geometry in order to obtain given max. temperature for known electrical current value. Also fuse holders had to be designed in such a way that the temperature on the junction between the wire and the fuse holder does not exceed max temperature of the wire insulation (90°C). The validity of numerical calculation results was verified by the experiments with fuse prototypes.

In Fig.4 and Fig.5 temperature and time behaviors of electrical wire, respectively are presented. In Fig.4 we show the temperature is in the junction between the conductor and insulation. This curve allows finding the maximal permissible temperature of the wire thus best to exploit the wire cross section in real applications. Fig.5 depicts the time, which is allowed for the electrical load given in the picture. This information is ideal if the wire is loaded finite time with higher current when the nominal current of the wire. Also this information is useful if the fuse has to be designed to protect the wire against overload currents. The results obtained in Fig. 4 and Fig.5 were also validated by the measurements.

7. CONCLUSIONS

1. The proposed method allows us to calculate heat transfer in electrical conductors using reduced 1-D model, which is completely satisfactory to investigate thermo-electrical behaviour of the conductors.

2. Applied implicit FV method enables us to approximate differential equations by applying energy conservation low directly to the mesh nodes. Therefore, it is maintained clear physical understanding while discretizing the differential equations. Also the method ensures both conservativeness and numerical stability of numerical scheme while having low computational time costs.

3. Using FVM, second order accuracy approximation was obtained for both governing equation and boundary conditions.

4. The analytical solutions are given for steady state regime, with some simplifying assumption. Although the heat convection coefficient a is assumed as constant value (that makes quite a deviation from correct value), the Eqs. (3.3), (3.11) are precise enough to calculate temperatures analytically.

5. The results of the proposed heat transfer mathematical model, boundary conditions and numerical approximation by implicit finite volume method give less than 10% error from experimental results.

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ŠILUMOS PERNEŠIMO UŽDAVINIO SPRENDIMAS CILINDRINIUOSE ELEKTROS LAIDUOSE IR SAUGIKLIUOSE NAUDOJANT NEIŠREIKŠTINĮ BAIGTINIŲ TŪRIŲ METODĄ

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Šiame darbe yra nagrinejamas netiesinis šilumos pernešimo uždavinys siekiant apskaičiuoti temperatūros pasiskirstymą cilindriniuose elektros laiduose bei saugikliuose naudojant neišreikštinį baigtinių tūrių metodą. Žinant temepratūros pasiskirstymą, vėliau galima efektyviau išnaudoti elektros laidų skerspjūvius bei patikimau apsaugoti pastaruosius nuo perkrovos srovių. Ši problema (laidų skerspjūvių minimizavimas) yra labai aktuali ten kur elektros laidinkų svoris turi būti minimizuotas (automobiliuose, laivuose ar lėktuvuose). Pasiūlyta skaičiavimo metodika supaprastina elektros laidininkų šiluminių-elektrinių charakteristikų apskaičiavimą nestacionariu atveju. Pagrindinis dėmesys šiame darbe yra skiriamas neišreikštinio baigtinių tūrio metodo pritaikymui šilumos laidumo uždaviniui spręsti. Netiesinės lygtys atsirandančios dėl netiesinių kraštinių sąlyų yra išspręstos naudojant Niutono iteracijų metodą. Stacionariame režime pateikti šilumos pernešimo lygties analitiniai sprendiniai apskaičiuoti temperatūros pasiskirstymą elektros laiduose bei saugikliuose.