3D Simulation of thermal field in the core of supercapacitor

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Abstract

From macrostructure of EDLC (Electrochemical double layer capacitor) it is possible to figure out, that for the heat conduction the volumetric properties of EDLC acts as anisotropic surroundings. This structure is in axial and radial direction of EDLC coil geometrically and physically different. Heat transfer through this structure is therefore different in axial direction against heat transfer in radial direction. At examined thermal model of EDLC, the waveform of axial and radial part of thermal coefficient (heat transfer by conduction) in the dependency on order of turn is designed. The graphical interpretation of results from simulation analysis that has been done in COMSOL environment is shown in second part of this paper.

1. Description of EDLC core

Cylinder interpretation of EDLC consists of 4 layers with different material properties, assembled in sandwich structure in this order:

- Carbon,
- Extruded aluminum
- Carbon,
- Separator.

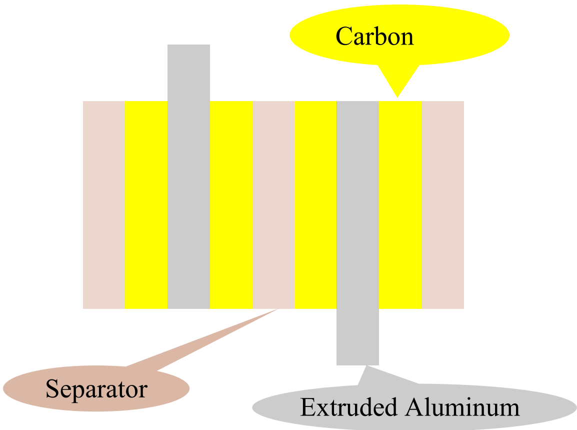

Fig. 1. Cross–section of EDLC structure

Label „n“ as total number of turns in four-layer structure and set $j \in \langle 1, n \rangle$ as order of sandwich turn. The diameter of turn is being changed in dependency on order of turn according to next formula:

$$r(j) = r_0 + (j-1)w \qquad (1)$$

where: r(j) – is internal diameter of turn in „j - th“ order,

r_0 – is diameter of first four-layer structure,

w – is width of one turn:

$$w = w_S + 2w_C + w_{Al} \qquad (2)$$

where, w_S – is width of separator layer, w_C – is width of carbon layer, w_{Al} – is width of extruded aluminum.

The area of bottom turn’s side with „j-th“ order is:

$$S(j) = \pi\left(r(j+1)^2 - r(j)^2\right) \qquad j \in \langle 1, n \rangle \qquad (3)$$

Axial part of turn’s thermal resistance with „j-th“ order was computed using next formula:

$$R_a(j) = \frac{L}{k_a(j).S(j)} \quad , \qquad (4)$$

where: L – is height of turn coil (m), k_a – thermal conductivity in axial direction (W/m.K)

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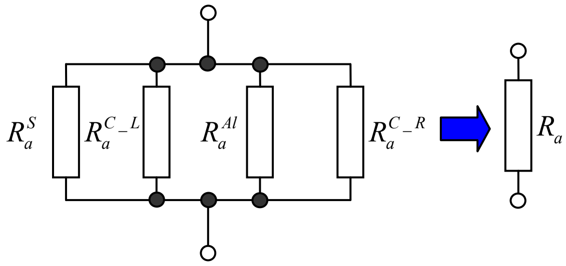

Fig.2. Structure of axial thermal resistances in one turn

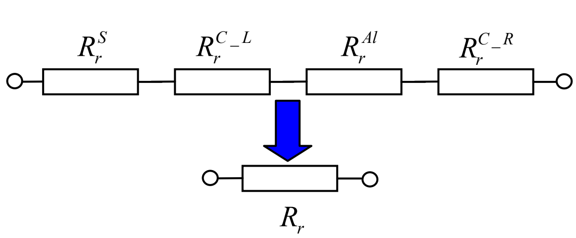

Fig.3. Structure of radial resistances in one turn

Axial thermal resistance of one turn in four-layer sandwich structure consists of four thermal resistances, which are shown on fig.2, whereby:

$R_a^{C\_L}$ - axial thermal resistance of carbon layer on left side, $R_a^{C\_R}$ - axial thermal resistance of carbon layer on right side, R_a^{Al} - axial thermal resistance of extruded aluminum layer, R_a^S - axial thermal resistance of separator layer.

For several thermal resistances in axial direction of thermal model shown on fig.2 is valid:

$$R_a^S(j) = \frac{L}{\pi.k_S\left(\left(r(j)+w_s\right)^2-\left(r(j)\right)^2\right)},$$

$$R_a^{C\_L}(j) = \frac{L}{\pi.k_C\left(\left(r(j)+w_s+w_C\right)^2-\left(r(j)+w_s\right)^2\right)},$$

$$R_a^{Al}(j) = \frac{L}{\pi.k_{Al}\left(\left(r(j)+w_s+w_C+w_{Al}\right)^2-\left(r(j)+w_s+w_C\right)^2\right)},$$

$$R_a^{C\_R}(j) = \frac{L}{\pi.k_C\left(\left(r(j)+w_s+2w_C+w_{Al}\right)^2-\left(r(j)+w_s+w_C+w_{Al}\right)^2\right)}, \tag{5}$$

k_S - thermal conductivity in separator layer, k_C - thermal conductivity in carbon layer, k_{Al} - thermal conductivity in extruded aluminum layer.

Equivalent axial thermal conductivity of one turn of EDLC shown on fig.2 is given by next equation:

$$\frac{1}{\mathrm{R_a}(j)} = \frac{1}{\mathrm{R_a^S}(j)} + \frac{1}{\mathrm{R_a^{C\_L}}(j)} + \frac{1}{\mathrm{R_a^{Al}}(j)} + \frac{1}{\mathrm{R_a^{C\_R}}(j)} \tag{6}$$

From equations (4,5,6) we can obtain dependency of thermal coeficient for heat transfer by conduction in one turn of EDLC with „j-th" order in next formula:

$$k_a(j) = \frac{L}{R_a(j).S(j)}. \tag{7}$$

Waveform of axial part of thermal coeficient in the scale of 100 turns is shown on fig. 4.

Total thermal resistance of one turn for „j-th" order in radial direction could be obtained from fig.3 as:

$$R_r(j) = R_r^S(j) + R_r^{C\_L}(j) + R_r^{Al}(j) + R_r^{C\_R}(j) \tag{8}$$

$R_r^{C\_L}$ - is radial thermal resistance of carbon layer on left side, $R_r^{C\_R}$ - is radial thermal resistance of carbon layer on right side, R_r^{Al} - radial thermal resistance of extruded aluminum layer, R_r^S - radial thermal resistance of separator layer.

After adding several radial resistances we can obtain dependency of equivalent radial thermal conductivity in one turn with „j-th" order as follows:

$$k_r(j) = \frac{\ln \dfrac{r_j}{r_{j-1}}}{2\pi L.R_r(j)} \quad (9)$$

Waveform of radial conductivity (9) in scale of 100 turns is shown on fig.5.

2. Simplified thermal model of EDLC in cylinder interpretation

3D geometrical model of EDLC capacitor in cylinder interpretation is shown on fig.6. It is representing the scroll coil of mentioned sandwich structure (fig.1) with diameter of 25 mm and height of 125mm. Compressed foils on top and bottom side are made from extruded aluminum and have prepared area for electrical contacts connection. Surroundings of EDLC model is air with temperature

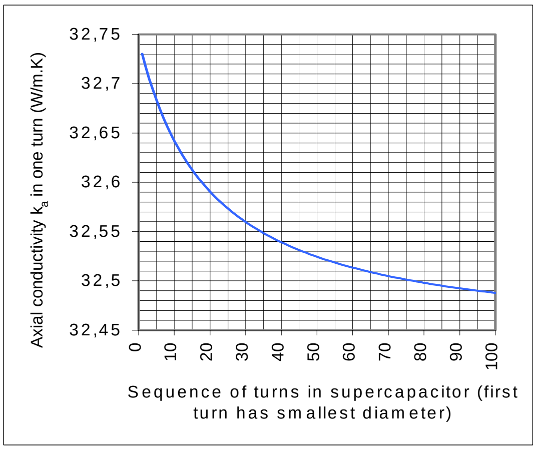

Fig. 4. Waveform of axial conduction in dependency on order of turn

Fig. 5. Waveform of radial conduction in dependency on order of turn

w = 130 μm, L = 125 mm, r_0=2,5mm

of 25˚ C. Heat power in the core EDLC is sets P=1 W.

To the each sub domain of EDLC the physical-thermal coefficients have been defined using material libraries from COMSOL heat-transfer module. Coefficient of core's thermal conductivity creates tensor of 2 grade in which part of axial and radial thermal conductivity are being included. The external sub domains of EDLC are adjusted to complex convection and radiation of heat transfer according to next formula:

$$n\left(k\nabla T\right) = q_0 + h\left(T_{inf} - T\right) + C_{const}\left(T_{amb}^4 - T^4\right) \quad (10)$$

Specify q_0 to represent a heat flux that enters the domain. $h(T_{inf} - T)$ models convective heat transfer with the surrounding environment, where "h" is the heat transfer coefficient and T_{inf} is the ambient bulk temperature. The value of h depends on the orientation of specific side in ambient:

- vertical wall,
- horizontal plane downside,
- horizontal plane upside.

$C_{const}\left(T_{amb}^4 - T^4\right)$ models radiation of heat transfer with the surrounding environment. T_{amb} is the temperature of the surrounding radiation environment, which might differ from T_{inf}. C_{const} is the product of the surface emissivity ε and the Stefan-Boltzmann constant σ = $5.669 \cdot 10^{-8}$ W/m^{2}K^4 (with the same unit as the Stefan-Boltzmann constant): $C_{const} = \varepsilon \cdot \sigma$

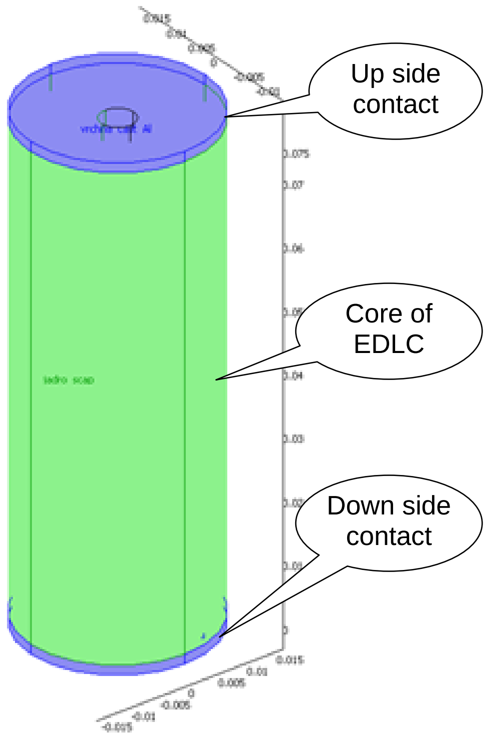

Fig.6. Geometrical model of EDLC created in COMSOL environment

3. Results of 3D simulation of the EDLC core

Graphical interpretation of surrounding's thermal distribution computation at the surface of EDLC is shown on fig.7. At the ambient temperature T_a=25˚ C the maximum temperature on the surface of EDLC is T_{max}=35,02˚ C and minimal temperature T_{min} = 34,15˚ C.

Graphical interpretation of internal temperature of EDLC in the direction of y-z axes is shown on fig. 8. At ambient temperature T_a=25˚ C the maximum temperature inside of EDLC is T_{max}=35,14˚ C and minimal T_{min} = 34,16˚ C.

From attached pictures it can be seen that thermal distribution is influenced by various value of thermal conductivities in axial and radial direction. The gradient of Temperature of heat transfer is different in mentioned direction in the rate of 1/20.

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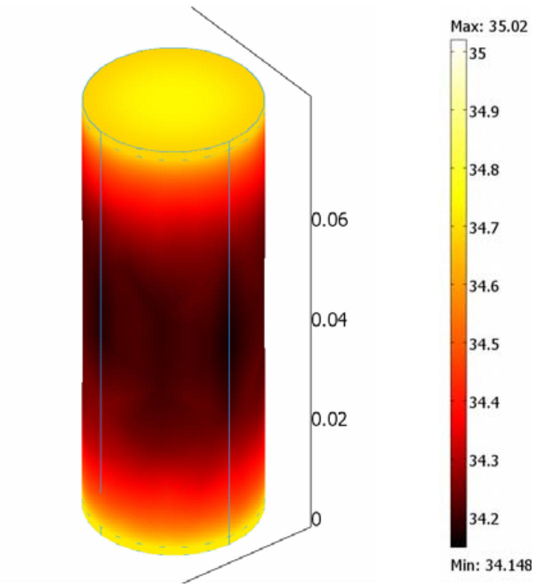

Fig.7. Space distribution of temperature on the surface of EDLC

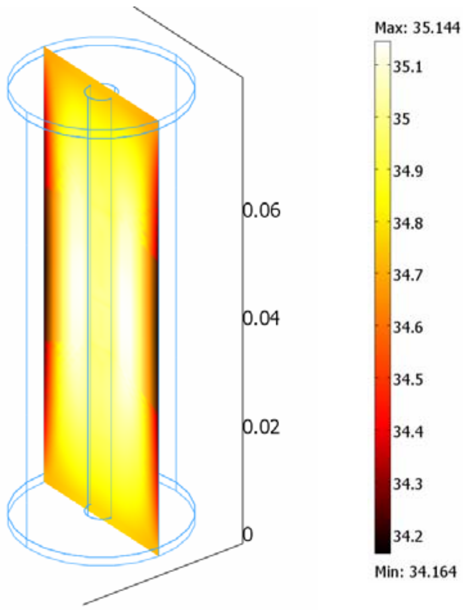

Fig.8. Distribution of EDLC internal temperature in the direction of y-z axes

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