# A COMPLETE 3D THERMAL MODEL FOR FAST FUSES

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***Abstract:*** **It is important to know the thermal behaviour of a fast fuse for an optimized design as well as for a right choice of the fuse rating with the aim to protect the power semiconductor device. A 3D thermal model was developed in order to study the temperature distribution at a fast fuse. In this model the thermal behaviour of the fast fuse depends on the design of the fuselink elements, the material parameters and the ambient conditions. It was shown the temperature distribution through all fuselink elements. The simulated temperatures were compared with measured temperatures at defined points on the fuse.**

***Keywords:*** **3D thermal model, simulation, fast fuse, temperature distribution.**

## 1. Introduction

Semiconductor power diodes were first marketed in 1953. It was realised from the outset that these devices had very limited overload capacities and, as they were expensive, the fuse manufacturers attempted to produce fuses which were more sensitive to overloads and which would operate more quickly than their conventional designs. As a result, the first applications were filed in 1955 for patents on fuses specifically designed to protect semiconductor rectifiers. The invention of the thyristor and the subsequent rapid expansion of the power electronics industry which it initiated, made the need for semiconductor fuses even more apparent.

Today, semiconductor devices are being manufactured with maximum continuous current ratings up to 4kA and peak inverse voltages of 6kV. Unfortunately, the devices still have poor overload capacities and continue to need sensitive and fast-acting protection.

## 2. Fuses for power semiconductor devices

The underlying principle associated with fuses is that a relatively short piece of conducting material, with cross-sectional area insufficient to carry currents quite as high as those which may be permitted to flow in the protected circuit, is sacrificed, when necessary, to prevent healthy parts of the circuit being damaged and to limit the damage to faulty sections or items to the lowest possible level. Fuses incorporate one or more current-carrying elements, depending on their current ratings, and melting of these, followed by arcing, occurs when excessive overcurrents flow through them. They can be designed to safely interrupt the very highest fault currents that may be encountered in service, and, because of the rapidity of their operation in these circumstances, they limit the energy dissipated during fault periods. This enables the fuses to be of relatively small overall dimensions and may also lead to economies in the cost and size of the protected equipment.

From power semiconductor devices' overcurrent protection point of view a special fuses were made, so called fast fuses. These kind of fuses have a distinct construction of the fuselinks because of their specific geometry.

Taking into account the thermal phenomena complexity for a fuse it is very difficult to study the heating processes both in steady-state or transitory operating conditions, using the traditional analytical equations. Approaches to simulate these processes have already been made in earlier work. In [1] the temperature distribution, and the thermal and electrical resistances of basic elements of the fuses are described by exact or semi-empirical analytical equations, and combined with iterative solution procedures. In [2, 3, 4] the fuselink is represented by an equivalent R-C network. Other simulations discretize the fuselink including its conductor according to Finite Element, in [5, 6, 7], or Finite Difference schemes, like in [8]. Because of the typical geometry of fuses a three-dimensional discretization is generally necessary, at least for the heat diffusion problem. In [9] a commercial FEM package has been used to model heating of relatively simple fuse geometries without notches and with one single notch, respectively. Other FEM work has been reported in [10, 11, 12]. In [13] a Windows based program code for modeling complete fuses, including M-Effect, using the Finite Volume Method, has been developed.

## 3. 3D thermal model of a fast fuse

During former work, because of limited computer capabilities, the authors had to concentrate on partial problems or on parts of the fuse geometry. The progress in computer technology enables the modelling and simulation of more and more complex structures in less time. It has therefore been the aim of this work to develop a 3D model of a complete fast fuse used for power semiconductor devices

 978-2-84516-363-8/07/$25.00 
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protection. The starting point is the power balance equation for each volume element dV, in the integral formulation:

$$\iiint \frac{j^2}{\sigma} dV = \iiint \rho c \frac{\partial T}{\partial t} dV - \iiint div(\lambda \cdot gradT) dV \quad (1)$$

where:

T means the temperature of element [ºC];
j – current density [A/m²];
σ – electrical conductivity [1/Ωm];
ρ – material density [kg/m³];
c – specific heat [J/kgºC];
λ – thermal conductivity [W/mºC].

The left term of before equation (it exists only in the fuse conductor elements), denotes the heating power from the current flow. It is in balance with the heat stored by temporal change of temperature, and the power removed from the element by thermal conduction. For the steady state temperature calculation, the heat storage term is zero, and the equation (1) becomes,

$$\iiint \frac{j^2}{\sigma} dV = -\iiint div(\lambda \cdot gradT) dV \quad (2)$$

The above equations are valuable only for internal volume elements because they don't take into account the surface convection.

A 3D model for a fast fuse has been developed using a specific software, the Pro-ENGINEER, an integrated thermal design tool for all type of accurate thermal analysis on devices. The subject was a fast fuse type aR with rated current by 400A, rated voltage about 700V and rated power losses of 65W. The 3D model had taken into consideration all the component parts of a fast fuse: outer cap, end tag, rivet, inner cap, ceramic body, fuselink and granular quartz, as shown in Fig. 1. It was considered a simplified geometry for the rivets.

The granular quartz which is filling up inside the ceramic body of the fuse have been modelled by a solid. This allow to use many small solid parts to fill all the gaps from the fuselinks.

## 4. 3D thermal simulation of the fuse

It was considered a typical application when this type of fast fuse is used to protect against overcurrents a three-phase power semiconductor rectifier. The current which flows through the converter branches and therefore through the fast fuses is about 315A. Taking into account that the rated power losses for the fuse is about 65W and the rated current is 400A, the rated resistance will be,

$$R_n = \frac{P_n}{I_n^2} = 0.4 m\Omega \quad (3)$$

Hence, at a current with the value of 315A results a power losses by,

$$P = R_n \cdot I^2 = 39.69 W \quad (4)$$

In this case, because the fuse has three fuselink elements and assuming an equal distribution of the current flow, every fuselink will dissipate 13.23W.

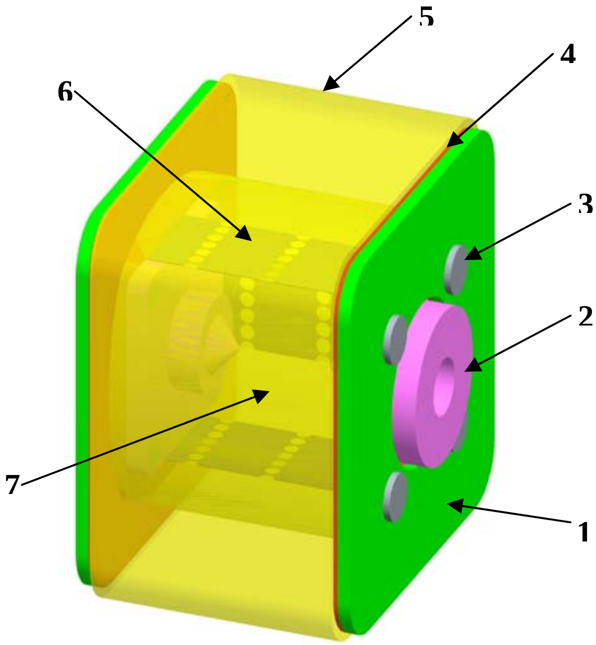


Fig. 1: Thermal model of the fast fuse (1 – outer cap; 2 – end tag; 3 – rivet; 4 – inner cap; 5 - ceramic body; 6 – fuselink; 7 – granular quartz).

For all thermal simulations a 3D finite elements Pro-MECHANICA software has been used. The material properties of every component part of the fuse are described in the table 1, according to Fig. 1.

The heat load has been applied on surfaces of the fuselink elements, 13.23W on every one. It is an uniform spatial distribution on these surfaces.

The mesh of this 3D fuse thermal model has been done using tetrahedron solids element types.

The analyzed fuse has the following overall dimensions: length: 50mm, square cross-section: 59mm x 59mm, end tag diameter: 24mm. The fuselink has a length of 38mm, width: 15mm, thickness: 0.15mm, notch diameter: 2.3mm. The ambient temperature was about 25ºC.

From experimental tests [3], it was computed the convection coefficient value for this type of fast fuse, $k_t$ = 4.247 [W/m²ºC]. Hence, it was considered the convection condition like boundary condition for the outer boundaries such as outer caps, end tags, rivets.


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Table 1. Material data and coefficients at 20ºC

| Parameter | Material | | | | | |
|---|---|---|---|---|---|---|
| | Ceramic body (5) | Copper (1, 2) | Iron FE40 (3) | granular quartz (7) | Silver (6) | Insulation material /pressed carton (4) |
| Density, ρ [kg/m$^3$] | 2400 | 8900 | 7190 | 1500 | 8210 | 1400 |
| Specific heat, c [J/kgºC] | 1088 | 387 | 420.27 | 795 | 377 | 0.099 |
| Thermal conductivity, λ [W/mºC] | 1 | 385 | 52.028 | 0.325 | 121.22 | 0.063 |

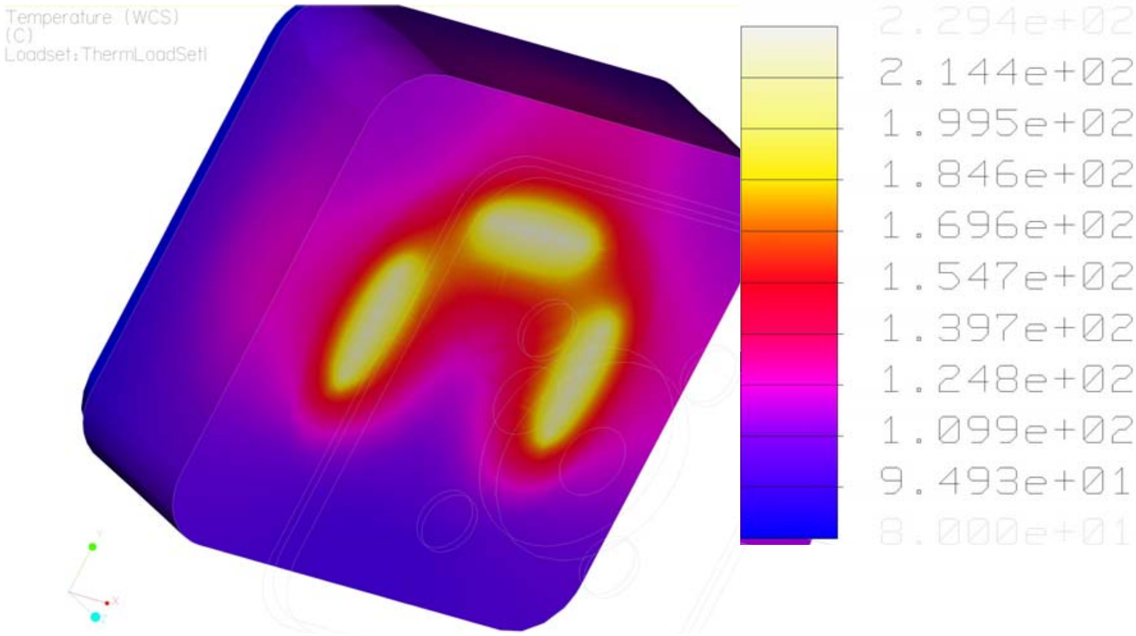


Fig. 2: Temperature distribution through the fuse at 50% cross section.

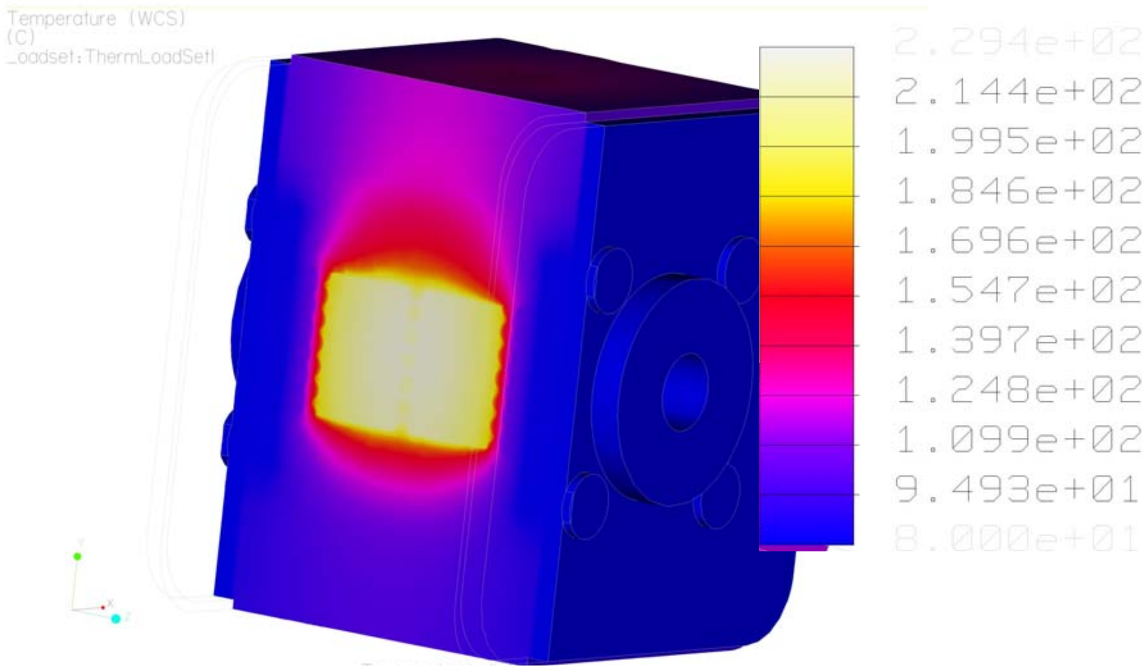


Fig. 3: Temperature distribution through left side fuselink at 24.45% cross section.


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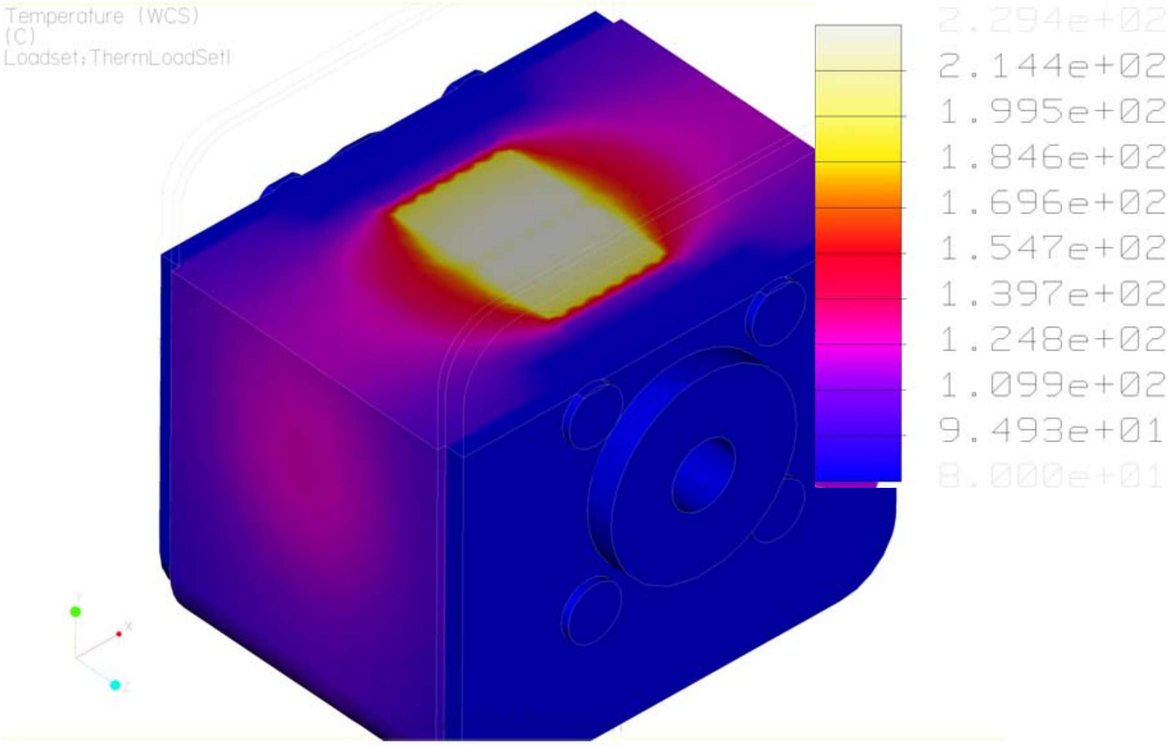


Fig. 4: Temperature distribution through upper side fuselink at 24.45% cross section.

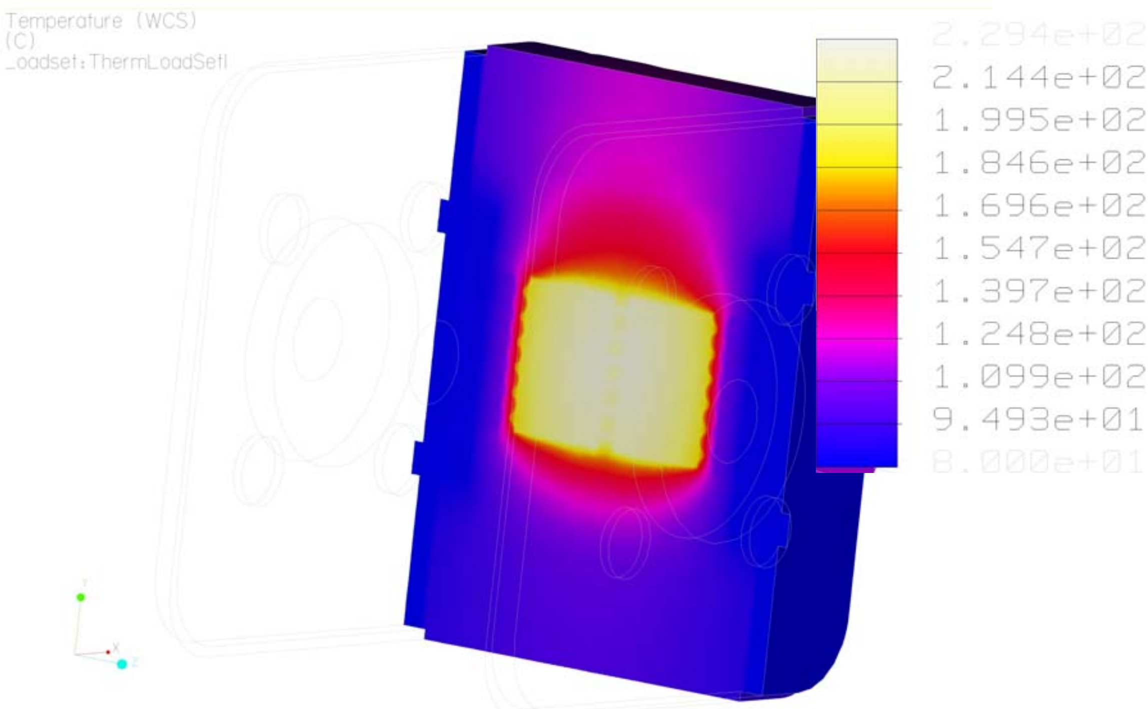


Fig. 5: Temperature distribution through right side fuselink at 75.55% cross section.

The convection coefficient has been applied on surfaces of outer caps, end tags and rivets, with an uniform spatial variation and a bulk temperature of 25ºC.

Further on, some steady state thermal simulations have been done. The temperature distribution inside the fuse is shown in the figures 2 to 5. The maximum temperature, on the fuselinks is 229.4ºC and the minimum, on the surface of the ceramic body, is about 80ºC.

As it can see from the pictures, the maximum temperature is obtained on the fuselink elements in the centre. This is explained because of the notches made on the fuselinks in order to clear the fault current as soon as possible and to interrupt the electric circuit without high overvoltages. It was assumed that every fuselink element has to dissipates the same quantity of heat, hence the maximum temperature is the same for every one. Of course, there is a thermal influence among these fuselink elements because of their geometrical site, figure 2.

Therefore, there are high temperatures around these fuselinks with the maximum in the middle of them.

Hence, it can observe high temperatures on the center surface of the ceramic body of the fuse depending on thermal conductivity of the fuselink elements (silver), filling material (granular quartz) and ceramic body.

To validate the 3D thermal model some experimental tests have been done in the same conditions like in the case of thermal simulation. A diagram with the electric circuit used for experimental tests is shown in Fig. 6.

The switch K, allow to supply with low-voltage the auto-transformer ATR, which adjusts the input voltage for the current supply CS. The main current from CS, flows through the fast fuse F, and will warm it. The current value is measured by an ammeter A, through a current transformer CT. Using proper thermocouples Th, it has measured the temperature on the fuse ceramic body on the proximity sides of the fuselinks. The measurement points were placed on the lateral sides and upper side of the fuse body, Fig. 7. The voltage signals from all thermocouples have been acquired and processed by a data acquisition board and a PC.

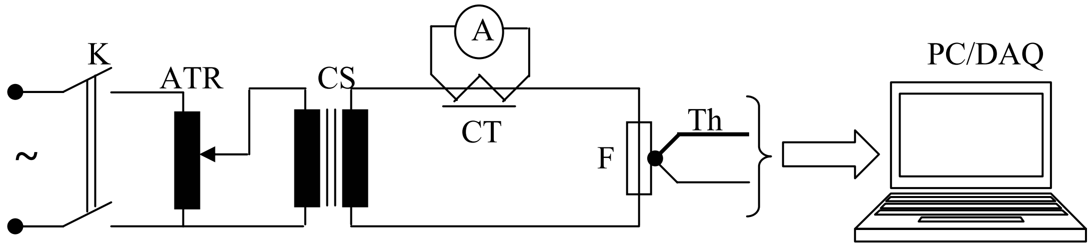


Fig. 6: Experimental tests electrical circuit

A comparison between experimental and simulation results is shown in the diagrams from figures 8 and 9. These represent the temperature variation on the body fuse surface against length of fuselinks (38mm). As it can observe from the graphics, there is a maximum temperature in the middle of the fuselinks and the minimum temperatures on the end-terminals of the fuse, because of the outer caps which act like simple heatsinks for the fuselink elements.

There are higher temperature values for the upper surface of the fuse (Texpb), as compared to lateral side (Texpa), because of the thermal influence of the lateral fuselinks. Of course, there are different temperature values resulted from experimental tests with respect to simulations (Tsima, Tsimb), because of measurement errors, thermal model simplifications, unbalanced current distribution through fuselinks and mounting test conditions. The thermal model has not included different types of busbar connections from geometricaly point of view.

Anyway, the maximum difference between experimental and simulation results is less than 3ºC.

## 5. Conclusions

Further on, the main conclusions of the simulation study as regards temperature distribution at fast fuses are presented.

- because of very complex thermal phenomenon the analysis of fast fuses thermal field can be done using a specific 3D FEM software (Pro-ENGINEER and Pro-MECHANICA); in this way it can be calculated the temperatures anywhere inside or on the fuse;
- it can observe a maximum temperature in the middle of fuselinks and the minimum values at the ends; also, there is a thermal influence among fuselinks that leads to different temperature values on the fuse surfaces;
- there is a good correlation between experimental and simulation temperature values;

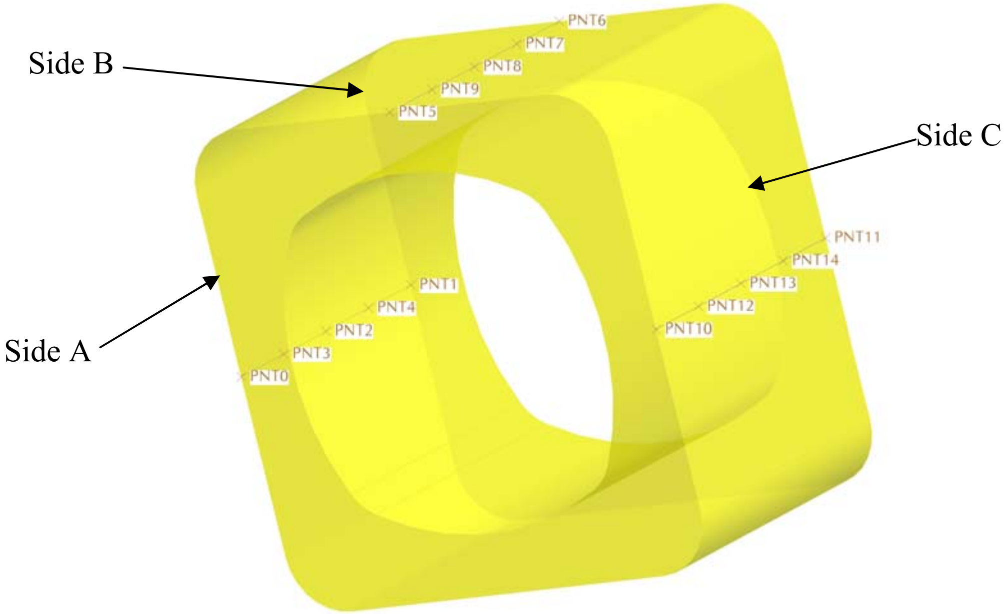


Fig. 7: Measurement points distribution on the surface of the fuse.

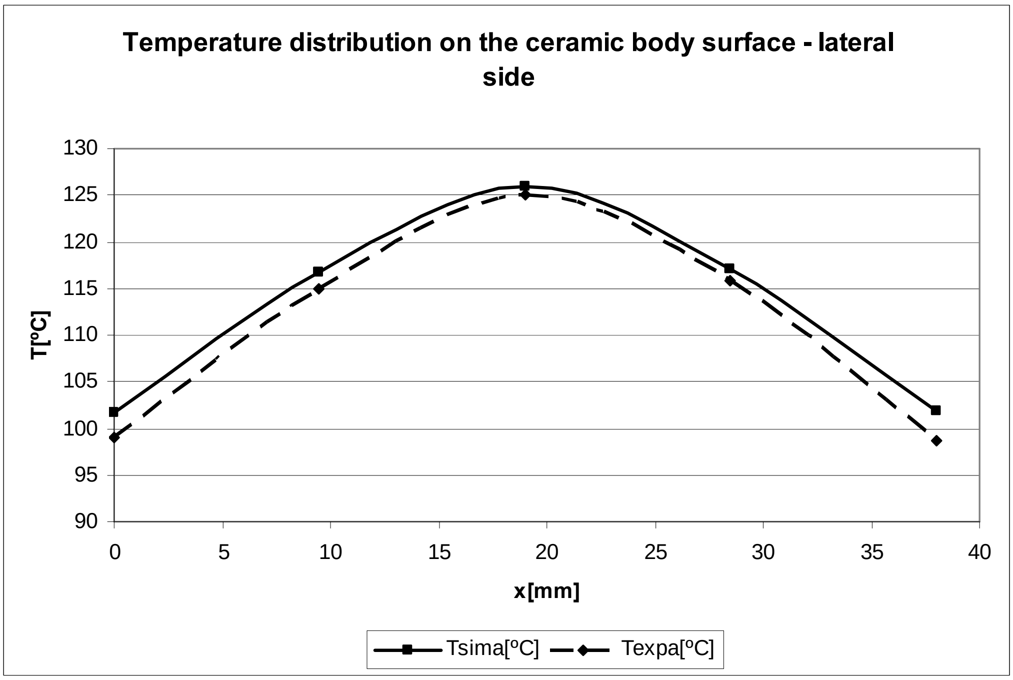


Fig. 8: Comparison between experimental and simulation temperatures vs. length of the ceramic body lateral side.

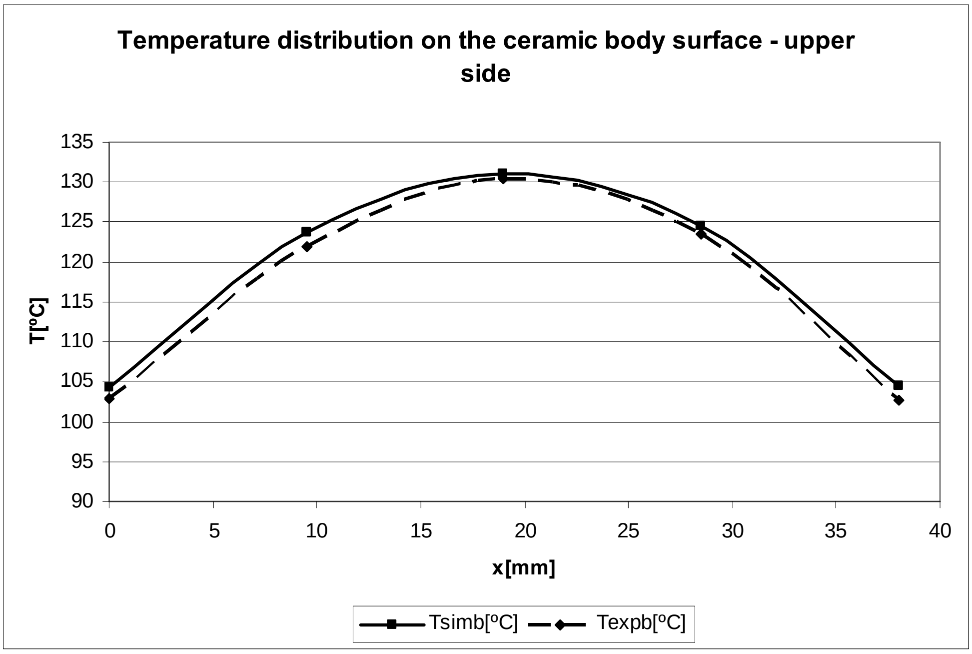


Fig. 9: Comparison between experimental and simulation temperatures vs. length of the ceramic body upper side.

- using the 3D simulation software it can improve the fast fuse designing and also there is the possibility to get new solutions.

## Acknowledgements

The author has a pleasure to acknowledge that described investigations were carried out in the frame of CEEX National Programme, Funding Application for Excellences Research Projects, Code project: 5, Contract no: 1489/07.04.2006.

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