HEATING OF FUSE-ELEMENTS IN TRANSIENT AND STEADY-STATE

K. Jakubiuk, W. Aftyka

Gdańsk University of Technology
Gdańsk, Poland
kjakub@ely.pg.gda.pl, waftyka@ely.pg.gda.pl

Abstract: Results of numerical calculations of fuse-element heating in transient and steady-state, performed in FLUX 2D software. The calculations take into account the heating of the whole fuse-element. Temperature in the fuse-element was chosen for analysis. Following the examinations performed, it was noted that during calculation of pre-arcing parameters, it is necessary to take heat conduction in the fuse-element into consideration, as well as the variable (as a function of temperature). In steady-state, the current density boundary value was determined, above which the fuse-element temperature begins to rise rapidly. Assumptions for the model and results of numerical calculations are given.

Keywords: electric fuse, heating, numerical modelling

1. Introduction

Heating of fuse-elements has been well examined by experimental methods [2]. However, experimentally, it is difficult to determine the temperature values and distribution inside the fuse. This difficulty can easily be overcome using a simulation method, which provides the information we want in a very short time [1,4]. However, the simulation method is not perfect. The main disadvantage of simulation methods are difficulties in determining the material, electrical and thermal properties, and especially their relation to temperature. The purpose of the paper is to check what errors are made during calculations of some of the fuse parameters using simplified relations given in literature, eg. [2]. In the paper, a simulation method was chosen for examination of fuse heating in transient and steady-state. Since this subject matter is very broad, the scope of research in this paper has been narrowed down to examining the distribution of temperature in the fuse-element. The scope of research includes also the determination of the effect of various simplifications, used mainly in analytical calculations to obtain a distribution of temperatures and to determine the effect of the shape and number of fuse-element constrictions on the heating process in transient and steady-state. Calculations were performed in FLUX 2D software [5]. The FLUX 2D package allows for analysis of coupled electromagnetic and thermal fields in transient. Steady-state were examined in such a way that the transient was analysed until the distributions of both fields became steady. The 2D package, used to examine fuse, allows for examination of axially symmetrical shaped fuse. Calculations in FLUX software are made in the finite element method in space and the method of finite differences as a function of time [5].

2. The model of the fuse-element and fuse

The source of heat in a fuse-element is Joule heat produced in the fuse-element. The fuse assumed for analysis (Fig. 1a) is axially symmetrical. Within the accepted symmetry, fuse-elements were assumed to have the shape of a wire (Fig. 1b) and of a cylindrical tube (Fig. 1c). Both fuse-element shapes had the same cross section area in the non-constricted part.

Tubular fuse-elements, though rarely used in fuses [2], allow to model the amount of heat given up from the fuse-element surface to the surroundings, by changing the tube diameter. Tube-shaped fuse-elements are equivalent to fuse-elements in the form of metal foil of various thicknesses and widths - but with the same cross-section area. The assumed constrictions in fuse-elements with two different shapes and various dimensions (Fig. 2) model various amounts of heat given off and taken away along the fuse-element.

Various simplifications of the model, consisting in consideration or neglection of heat exchange between various areas of the fuse, can be introduced through appropriate boundary conditions or by assigning appropriate values to thermal conduction coefficients λ_k for the k-th area of the fuse [3]. In transient, the following boundary conditions were modelled in this way:

a) no heat is carried off - adiabatic heating ($\lambda_1 = \lambda_2 = 0$),
b) heat is carried off along the fuse-element to the contacts ($\lambda_2 = 0$),

c) heat is carried off to the contacts and to the surroundings.

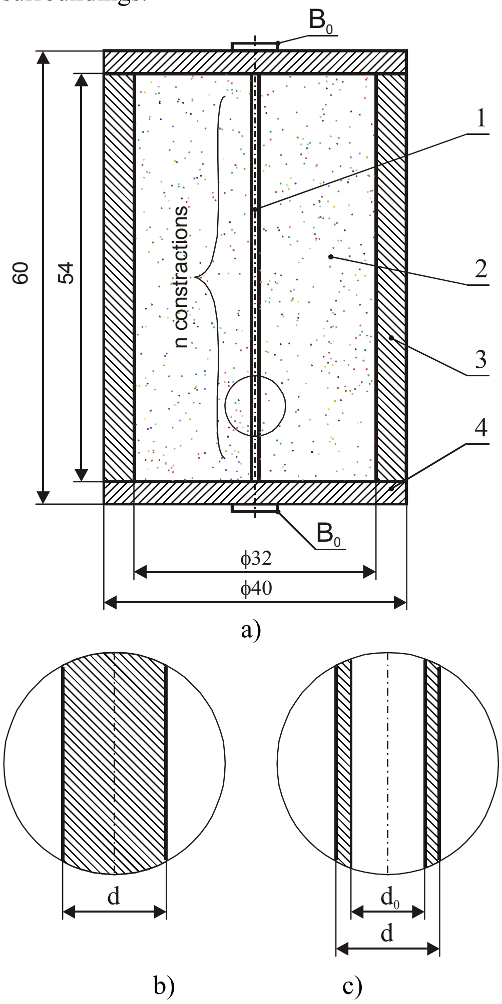


Fig. 1. Fuse assumed for analysis
a) fuse cross section, b) wire fuse-element (cross-section area - 0.75 mm^2), c) tubular fuse-element (cross-section area - 0.75 mm^2)
1 – fuse-element, 2 – sand, 3 – isolation tube, B_o – current feed surface

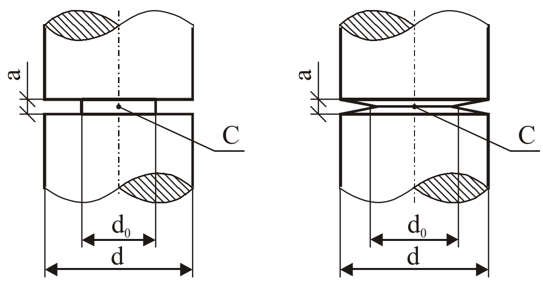


Fig. 2. The examined shapes of constrictions in a wire-shaped fuse-element
a) rectangular, b) triangular
denotation of a rectangular constriction: „r-0.2" for a=0.2d and „r-1" for a=d
denotation of a triangular constriction: „t-0.2" for a=0.2d and „t-1" for a=d

In steady-state, we can, of course, consider only variant b) or c). Heat transfer from the fuse-element takes place through thermal conduction, while from the fuse casing to the surrounding air – by convection [3], according to the formula

$$q_k = \alpha_c (T_{3p} - T_o) \qquad (1)$$

where: α_c – coefficient of heat loss, T_{3p} – temperature of the fuse surface, T_o – temperature of the surroundings.

Giving up heat from the contacts was modelled in such a way that a constant temperature was assumed at part of the contact area – marked in Fig. 1 by the symbol B_o. In both transient and steady-state, heating was examined until the moment when the maximum temperature in the fuse-element reached melting point. During heating to a higher temperature, fuse-element disintegration may take place and then the manner of its heating will change [1].

2. Fuse-element heating in transient

2.1. The model of fuse-element heating

In order to examine the fuse-element heating process in transient, it was assumed that current densitiy at the ends of the fuse-element is homogeneous, and increases in a linear manner as a function of time, in accordance with the formula

$$j = At \qquad (2)$$

where: A – rise steepness of current density increase, t – time.

An approximately linear character of current escalation, especially during the initial phase, occurs most frequently in short-circuit currents and is convenient for comparison of fuse-element heating in various conditions. For fuse-element cross-section dimensions occurring in practice, we can neglect the skin effect in calculations of the current density distribution in the fuse-element (the depth of penetration of the electromagnetic field is greater than the cross-section dimensions of the fuse-element) and assume that at any moment, the quasistatic distribution of potential $\varphi(t)$ in the fuse-element is described by the formula [1]

$$\nabla \cdot (\sigma \nabla \varphi) = 0\,, \qquad \mathbf{j} = \sigma \nabla \varphi \qquad (3)$$

where: $\mathbf{j}$ – the vector of current density, $\sigma = \sigma(r,z,T)$ – conductivity dependent on co-ordinates and temperature in accordance with the formula

$$\sigma(r,z,T) = \frac{\sigma_o}{1 + \alpha\,[T(r,z,t) - T_o]} \qquad (4)$$

Distribution of temperature in the fuse-element is described by the equation of thermal conductivity

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T + \frac{j^2}{\sigma} \quad (5)$$

where: ρ - density of the medium, c_p – specific heat, λ – thermal conductivity, j – module of current density.

In the remaining areas of the fuse, the temperature distribution is described by the formulae (5), which omit the last component (there is no heat source). If in formula (5) we omit the second component on the right, the heating will have an adiabatic character. Distributions of temperature in particular areas of the fuse are connected by appropriate boundary conditions. For current density, a homogeneous distribution at the ends of the fuse-element was assumed as a boundary condition, described by relation (2). In particular areas of the fuse-element, the assumed material data and coefficients [1] are given in table 1.

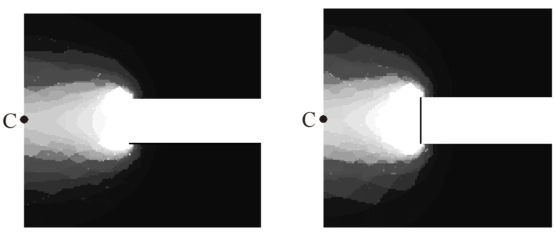
Table 1. Material data and coefficients

Parameter	Designation of material – Fig. 1			
	1	2	3	4
λ, W/(m·K)	396	1,2	1	396
c_p, J/(kg·K)	386	80	800	386
ρ, kg/m^3	8930	1500	2400	8930
α_c, W/(m^2·K)	-	-	10	-
σ_0, S/m	$5{,}98 \cdot 10^7$	-	-	$5{,}98 \cdot 10^7$
α, 1/K	0,0039	-	-	0,0039

2.2. Calculation results

In the process of fuse-element heating in transient, an important parameter is time until melting point (T_m). In order to determine the effect of various factors on fuse-element heating, the results obtained were compared with the results obtained for adiabatic heating. The results were compared for identical values of parameter A (2) at point C of the fuse-element constriction (Fig.2). Calculations were performed for parameters of the fuse-element given in table 1.

Fig. 3 presents an example of temperature distribution at the instant when $T_{max}=T_m$ in the area of fuse-element constriction r-0.2 (Fig. 2) for various values of parameter A and various conditions of heat transfer from the fuse-element.



a) b)

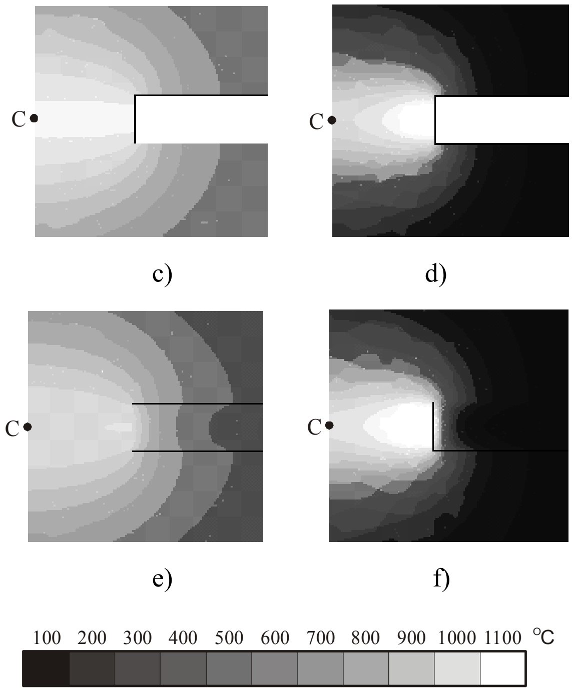


Fig. 3. Temperature distribution in the fuse-element in the constriction area r-0.2 for A=10 kA/(mm^2·ms) (a,b,c) and A=1000 kA/(mm^2·ms) (d,e,f) during adiabatic heating (a,d) heat being carried off along the fuse-element (b,e), and heat being carried off along the fuse-element and into the surroundings (c,f)

Fig. 4÷7 present results of simulation of temperature, time until melting point (T_m) and pre-arcing Joule integral (I^2t_p) as a function of various parameters of the fuse-element and parameter A (2).

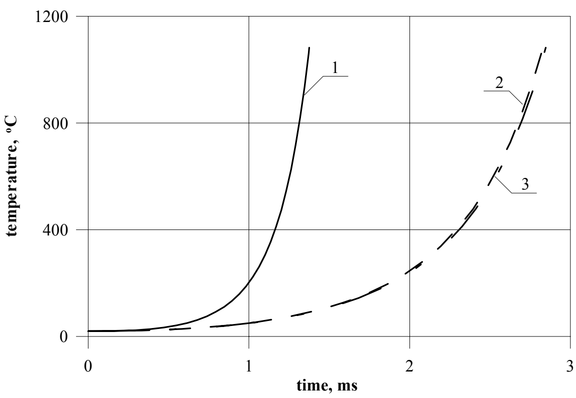


Fig. 4a. Trace of temperature at point C as a function of time, constriction 1:5, shape r-0.2, A=10 kA/(mm^2·ms)
1 – adiabatic heating, 2 – heat carried off only to the contacts, 3 – heat carried off to contacts and to surroundings

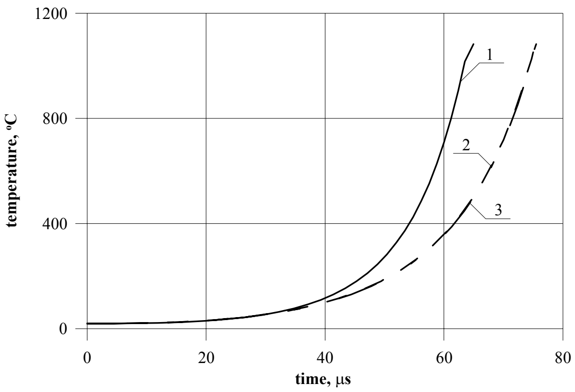
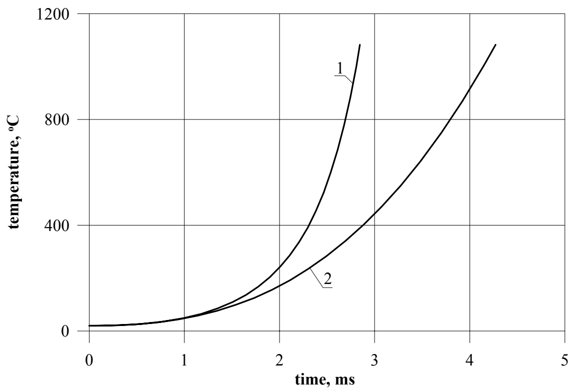
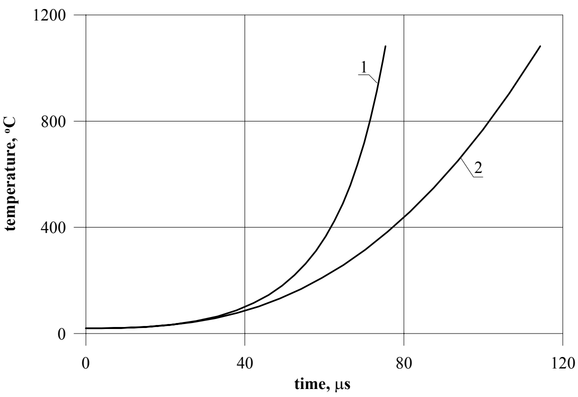


Fig. 4b. Trace of temperature at point C as a function of time, constriction 1:5, shape r-0.2, A=1000 kA/(mm^2·ms);
1 – adiabatic heating, 2 – heat carried off only to the contacts, 3 – heat carried off to contacts and to surroundings



a)



b)

Fig. 5. Trace of temperature at point C as a function of time for constriction 1:5, shape r-0.2:
a) A=10 kA/(mm^2·ms), b) A=1000 kA/(mm^2·ms)
1 – $\sigma=\sigma(r,z,T)$=var, 2 – $\sigma=\sigma_o$=const.

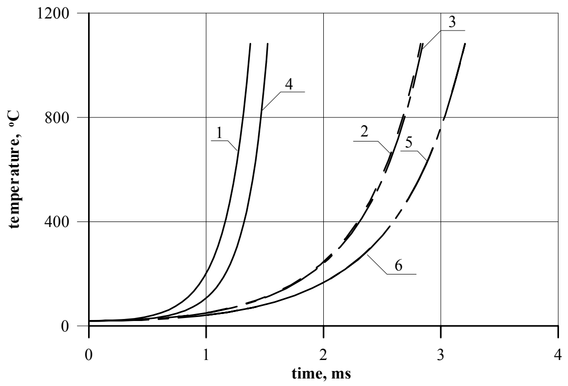


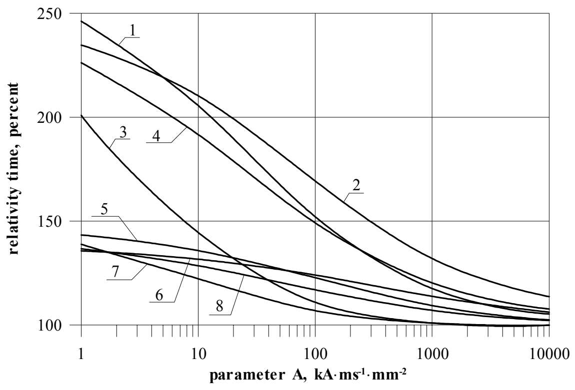
Fig. 6. Trace of temperature at point C as a function of time for: constriction 1:5, A=10 kA/(mm^2·ms)
1 – adiabatic heating – r-0.2, 2 – heat carried off only to the contacts – r-0.2, 3 – heat carried off to contacts and to surroundings – r-0.2, 4 – adiabatic heating – t-0.2, 5 – heat carried off only to the contacts – t-0.2, 6 – heat carried off to contacts and to surroundings – t-0.2

Heating of the fuse-element constriction (Fig. 4) depends largely on the value of parameter A and on the conditions of heat transfer from the fuse-element. In transient, heat transfer to sand, compared with heat transfer along the fuse-element, is practically insignificant. As could be expected, the effect heat transfer along the fuse-element is the greater, the smaller the value of A is.

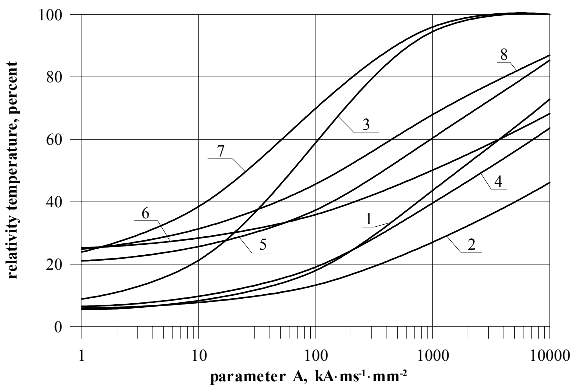
Accounting for variable conductivity as a function of temperature (Fig. 5) has a serious effect on fuse-element heating calculations. Assumption of constant conductivity, independently of the value of parameter A, causes considerable extension of time until melting point, and so, an increase of I^2t_p.

During calculations of fuse-element heating tor an element with several constrictions (in transient), for various parameters, mutual interaction between constrictions in the heating process was not noted. The effect of constriction shape on its heating is shown in Fig. 6. This effect is not significant and plays a more important role during adiabatic heating. The constriction length influences the amount of heat given off in the constriction, while the shape effects the current density in the constriction. In Fig. 6 the different traces result from different current density distribution in both cases. As the value of parameter A grows, the differences between the traces decrease. Comparative, relative results of temperature calculation, time until melting point T_m and I^2t_p as a function of parameter A for various conditions are presented in Fig. 7. All the calculated magnitudes are related to the same magnitudes calculated for adiabatic heating. Variable conductivity as a function of temperature has been taken into account.

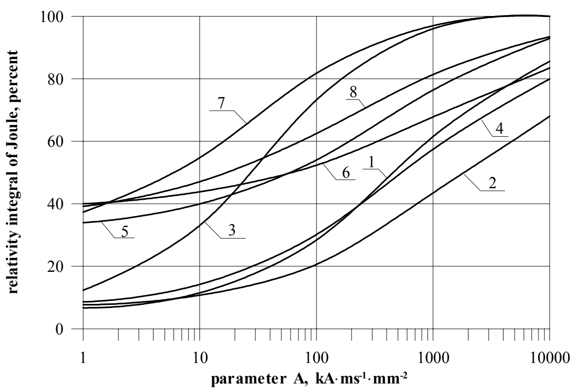
It ensues from Fig. 7a, that at small values of A, time until T_m is considerably longer when heat is carried away from the fuse-element, than during



a)



b)



c)

Fig. 7. Dependencies between relative values: time until T_m at point C - a) temperatures at point C at the instant of reaching T_m during adiabatic heating - b) and I^2t_p - c) when heat is carried off to the contacts and to the surroundings, related to the same magnitudes during adiabatic heating, and parameter A
1 – constriction 1:5, shape r-0.2; 2 – constriction 1:5, shape t-0.2; 3 – constriction 1:5, shape r-1; 4 – constriction 1:5, shape t-1; 5 – constriction 1:2, shape r-0.2; 6 – constriction 1:2, shape t-0.2; 7 – constriction 1:2, shape r-1; 8 – constriction 1:2, shape t-1

adiabatic heating (for A=10 kA/(mm^2·ms) relative time is from 105 to 210%). Relative time is greater for larger fuse-element constrictions and for triangular constriction shape, which results from a nonhomogeneous current density distribution. For values of parameter A > 1000 kA/(mm^2·ms) we can assume that heating until T_m is practically adiabatic.

The relations presented in Fig. 7b indicate what relative temperature (relative to T_m) is reached at point C at the instant when T_m is achieved during adiabatic heating. The lowest temperature occurs at point C, at low value of A, large constriction (1:5) and with a triangular shape of the constriction, while the highest temperature occurs for high value of A, small constriction - 1:2 and rectangular shape of the constriction. Such dependencies of relative temperature result mainly from the conditions in which heat is carried off, and from current density distribution in the constriction. At small values of parameter A, especially in a large constriction of little length, a large amount of heat has enough time to be carried off from the constriction into the surroundings. For greater values of A, the amount of heat carried off into the surroundings is smaller. With a triangular constriction, the current density distribution is more nonhomogeneous in the constriction area and this is why the temperature at point C is lower than in the case of a rectangular constriction.

The dependency between relative value I^2t_p and parameter A is similar to the dependency between relative temperatures (Fig. 7c). The values of I^2t_p have been related to I^2t_p during adiabatic heating calculated to the moment when T_m is reached at point C. Qualitatively, these dependencies are almost identical, but they differ quantitatively. Quantitative differences result from the fact that, at a given value of A, the relative temperature depends both on duration of heating and on changes of conductivity (4) during this time, while the Joule'a integral depends only on the duration of heating. Therefore, relative values of I^2t_p are greater than the relative values of temperature in the same conditions.

It ensues from the traces shown in Fig. 7 that calculations of pre-arcing time, pre-arcing Joule integral and temperature distribution in the fuse-element in transient state should be performed, taking into account the process of heat transfer from the fuse-element and variable conductivity [3]. Calculations made using simplified relations lead to considerable errors, especially for small values of parameter A.

3. Heating of the fuse-element in steady-state

3.1. The model of fuse-element heating

The fuse-element heating process in steady-state is described by formula (5), in which the component on the left equals zero. However, due to the fact that, the *Steady thermal* module of the FLUX software package lacks the possibility to account for the dependence between conductivity and temperature [5], steady-state in the fuse-element was analysed in such a way, that calculations were performed for the transient until temperature distributions in the fuse-element steadied. It was assumed that current density at the ends of the fuse-element is homogeneous and has an exponential trace, in accordance with the formula

$$j = J_o[1 - \exp(-\frac{t}{T_o})] \quad (6)$$

Current density J_o (6) may express direct current density, as well as the effective value of a current changing periodically as a function of time. In the second case, the current change period should be considerably shorter than the time constant T_o. With this assumption, for alternating current, temperature changes connected with current change period are not accounted for.

3.2. Calculation results

In the process of fuse-element heating in steady-state, temperature distribution depends on many parameters. In the paper, the effect of current density J_o (6), fuse-element dimensions and the degree and number of constrictions on temperature distribution in the fuse-element was examined. The effect of the constriction shape was not examined. The effect of the number of constrictions on temperature was investigated. In steady-state, a very important role is played by the manner in which heat is carried off from the fuse-element. It was assumed that heat transfer from the fuse-element takes place through convection – from the surface (excluding the contact faces from which heat is carries away by means of thermal conductivity) B_o (Fig. 1). The effect of various parameters of heat transfer from the fuse on the temperature distribution in the fuse-element was not examined.

Selected results of calculations of the temperature in the constriction located in the mid-length of the element are presented in Fig. 8÷11.

It results from Fig. 9÷11 that for a given fuse-element, there exists a certain boundary current density value, above which the temperature of the constrictions, and therefore the temperature of the entire fuse-element, begins to increase rapidly. $J_{og} \approx 100$ A/mm^2 can be assumed as the current density boundary value for the given fuse-element. The value of J_{og} allows us to determine eg. sustained boundary current for a given fuse [2].

From Fig. 9, it ensues that failing to account for variable conductivity in calculations leads to large errors, especially for current densities $J_o > J_{og}$.

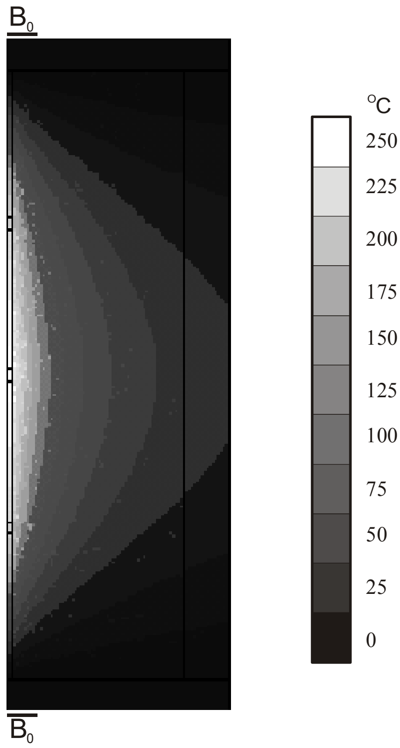


Fig. 8. Distribution of temperature in the fuse in steady-state for J_o=100 A/mm^2 (wire element, n=3, constriction 1:5)

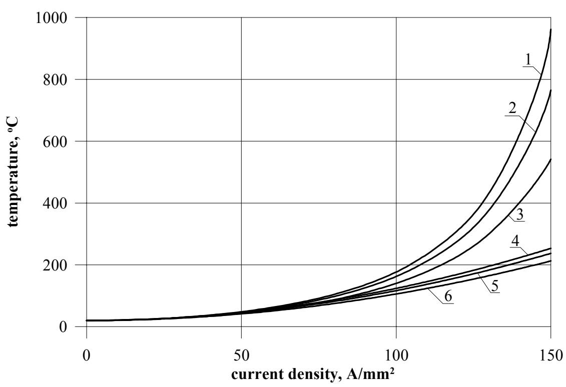


Fig. 9. The relation between temperature in the fuse-element constriction 1:5 as a function of current density J_o for n=1 and:
$\sigma=\sigma(r,z,T)$=var: 1 – wire fuse-element, 2 – tubular fuse-element with 0.2 mm thickness, 3 – tubular fuse-element with 0.1 mm thickness;
$\sigma=\sigma_o$=const.: 4 – wire fuse-element, 5 – tubular fuse-element with 0.2 mm thickness, 6 – tubular fuse-element with 0.1 mm thickness

If the condition $J_o > J_{og}$ is met in a given fuse, heat transfer from the fuse-element to the sand medium plays an important role (Fig. 10 and 11). The temperature of the fuse-element with a larger surface area (tubular element) builds up more rapidly than in a fuse-element with a small surface area (wire-element).

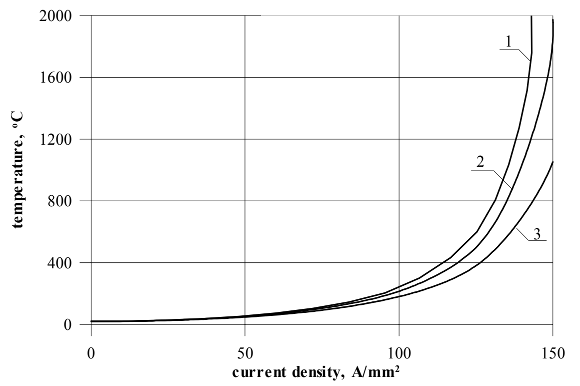


Fig. 10. The relation between temperature in the 1:5 constriction as a function of current density J_o for: n=3 and σ=σ(r,z,T)=var
1 – wire element, 2 – tubular fuse-element with 0.2 mm thickness, 3 – tubular fuse-element with 0.1 mm thickness

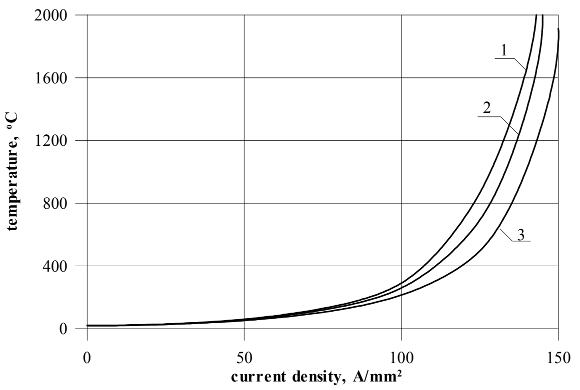


Fig. 11. Relation between temperature in the fuse-element constriction 1:5, as a function of current density J_o for: n=5 and σ=σ(r,z,T)=var
1 – wire element, 2 – tubular fuse-element with 0.2 mm thickness, 3 – tubular fuse-element with 0.1 mm thickness

If the $J_o > J_{og}$ is met, the number of constrictions in the fuse (Fig. 9 ÷ 11), has a significant effect on the temperature in the constrictions.

The time necessary to achieve steady-state of temperature in the examined fuse-element can be assumed as equal to 10 minutes.

4. Summary and conclusions

The following conclusions result from the considerations and calculations performed:

a) regarding fuse-element heating in transient:

- calculations should take into account the variable conductivity of the fuse-element as a function of temperature. Otherwise, serious errors are made;
- at low current densities, heat transfer from the constrictions to the unconstricted parts of the fuse-element should be taken into account;
- the degree of constriction plays a significant role;
- the shape of the constriction plays a small role resulting from nonhomogeneous distribution of current density in the constriction. Greater nonhomogeneity occurs in short constrictions;
- transfer of heat from the fuse-element to the surrounding sand does not play a significant role.

b) regarding fuse-element heating in steady-state:

- there exists a boundary value for current density in the fuse-element, above which its temperature will begin to rise rapidly;
- calculations should account for variable conductivity as a function of temperature. Otherwise, serious errors can be made;
- the temperature of the fuse-element, especially at current densities greater than the boundary density, is affected by the number of constrictions.

Acknowledgement

Authors have a pleasure to acknowledge that described investigations were carried out in the frame of project no 8 T10A 05821 sponsored by the Polish Committee of Scientific Research.

References

[1] Jakubiuk K.: Electrical explosion and implosion of conductors. Technical University of Gdańsk Publishing 2000.

[2] Lipski T.: Bezpieczniki niskonapięciowe. Warszawa. WNT 1968 (in Polish).

[3] Sasu M., Oarga G.: Simulation of the heat transfer phenomena in variables section fusible elements in non-adiabatic regime. Springer-Verlag 1992.

[4] Zhang Juan, Ma Zhiying: Mathematical model of two dimensional temperature field and its application in high-voltage current-limiting fuse-link. Power System Technology. Vol. 19, No 12, Dec 1995.

[5] Flux 2D. User's guide. Version 7.30.