AN ANALYTICAL MODEL OF POST - ARC FULGURITE RESISTANCE OF H.B.C. FUSES

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Abstract: 1D simplified cylindrical model of post-arc fulgurite cooling resulting in its resistance growing has been given. Assumptions to the model were taken from our previous experimental results. Additional tests of which goal was the dynamic temperature measurement in the vicinity of fulgurite are described. The basic heat transfer equation is solved using Crank-Nicolson scheme. The results of calculations of the temperature and fulgurite resistance in time are compared with the experimental ones. The agreement of both is satisfactory.

1 Introduction

Existing analytical approaches on h.b.c. fuses cover practically two problems: pre-arcing heating, e.g. [1,8] and arcing behaviour, e.g. [4]. Parameters of the arcing processes, particularly at the arc-quenching instant define initial conditions of the post-arc period. A h.b.c. fuse during interrupting a short-circuit current usually brings it to the artificial zero. Immediately after that the post-arc channel gets cooling, the vapour condensation begins and then the glass solidification and finally the fulgurite creation have take place. However, a dynamic of these processes was already investigated experimentally [2,3,5], the knowledge of them still is insufficient to derive a complete analytical approach. On the other hand, a preliminary analytical model on the base of mentioned investigations can be elaborated. It is the main aim of the paper.

The results of already mentioned investigations [3,5] show that the post-arc fulgurite resistance strongly relates to the temperature. That's why the heat transfer in connection with the post-arc fulgurite cooling is the principal problem to deal with in this approach. Of course, a verification of the analytical results by a comparison with the experiments is also included into the paper. But to have a possibility to make better confirmation of both results some additional experiments are needed. A brief description of these experiments is therefore the subject of next section.

2 Additional experiments

In addition to experimental results given in [2,3,5] it was decided to monitor the temperature in the vicinity of the fulgurite. Indicated in Fig. 1 tested fuse-link shown in our paper [3] was completed by a thermocouple. The test scheme remains the same. During shots the post-arc current was monitored by a transient recorder over 0.5 s, whereas the temperature up to 30 s of post-arc period. The recorded temperature and resistance profiles are shown in chapter 3. Fuse link and -element dimensions and short circuit test conditions are given in [3].

3 Models of temperature field and post - arc resistance

1D model for temperature distribution has been considered. So simple approach was dictated mainly by the lack of information about properties of SiO_2 sand and of fulgurite above $1000^{o}C$ [4,6,7,9,10]. Unfortunately, especially about chemicals compositions of a fulgurite, we know nearly nothing, hence its physical properties are also not know sufficiently [2,5,10]. So, because of 1D model and practically lack of needed physical informations the following considerations are preliminary and give qualitative view rather than quantitative.

Investigated fuse-link model (Fig. 1) pertains to a link with the strip fuse-element of 3 constrictions. The fulgurite after such an element, of course, is not circular in its cross-section. Above that it is changeable along axis. In spite of that it has been assumed that the fulgurite in shape is cylindrical (Fig. 1b). Diameters of the fulgurite layers shoving different properties were defined by averaging of their real dimensions. To minimise a calculating error due to axial heat transfer it was decided to neglect the parts in the vicinity fuse-link contacts (Fig. 1a). The temperature distribution for above model describes the equation

$$\rho_n c_n \frac{\partial T_n}{\partial t} = \nabla\left(\lambda \nabla T_n\right) \tag{1}$$

where: $\rho_n(T)$ - specific density, $c_n(T)$ - specific heat, $\lambda_n(T)$ - heat conductivity, n - layer number.

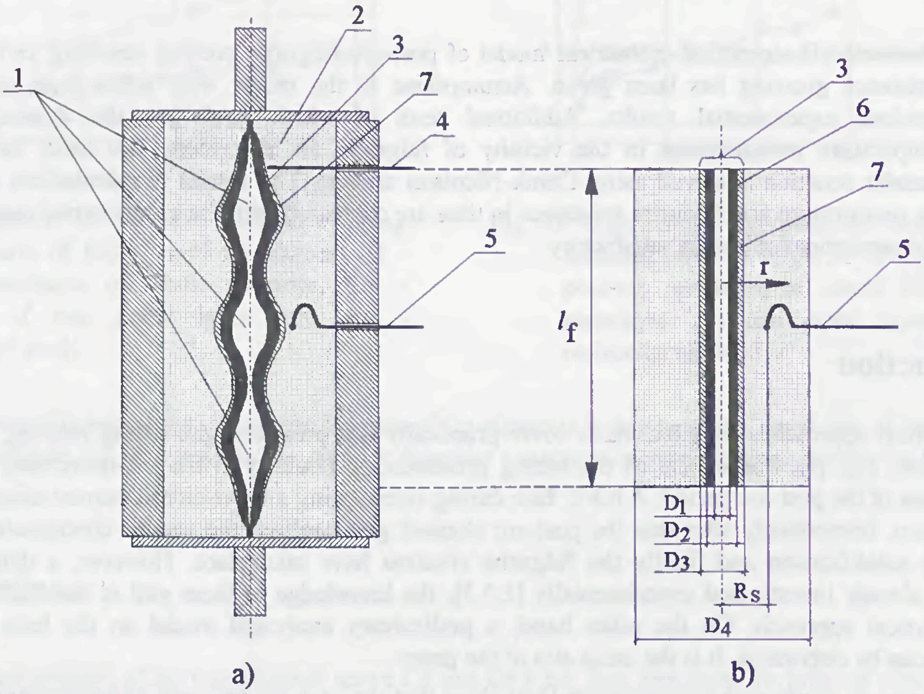


Fig. 1 Investigated fuse-link: a) - physical model, b) - model for calculation: 1 - space after exploded notch, 2 - quartz sand, 3 - fulgurite shell, 4 - voltage probe, 5 - thermocouple, 6 - fully melt layer, 7 - partial melted layer.

For 1D the equation (1) gets the form

$$\rho_n c_n \frac{\partial T}{\partial t} = \lambda_n\left(\frac{\partial^2 T_n}{\partial r^2} + \frac{1}{r}\frac{\partial T_n}{\partial r}\right) + \frac{\partial \lambda_n}{\partial r}\frac{\partial T_n}{\partial r} \tag{2}$$

As the initial condition is an arbitrary assumed initial temperature distribution due to fuse-link heating up during pre - and arcing period, one can write

$$T_n\big|_{t=0} = T_{n0}(r) \tag{3}$$

The boundary conditions were assumed as follows

$$\left.\frac{\partial T_1}{\partial r}\right|_{r=\frac{D_1}{2}} = 0 \qquad \left.T_3\right|_{r=\frac{D_4}{2}} = 0 \tag{4}$$

Second condition of (4) is an approximation taken due to unknown coefficient of heat take over by the fuse-link body. By not large temperature rises on the body inner surface this approximation does not introduce significant errors. The displacement of the melting (or solidification) boundary of sand defines the equation

$$\rho_1 L_m v_m = \left(-\lambda_1 \frac{\partial T_1}{\partial r} + \lambda_2 \frac{\partial T_2}{\partial r} \right)\Bigg|_{r=\frac{D_2}{2}} \qquad (5)$$

in which: L_m - melting heat, v_m - velocity of displacement boundary between liquid and solid state, T_1 - liquid temperature, T_2 - solid state temperature.

The fulgurite resistance in time defines the formulae

$$R = l_f \left(2\pi \int_{\frac{D_1}{2}}^{\frac{D_4}{2}} \sigma_n \, r \, dr \right)^{-1} \qquad (6)$$

where: l_f - fulgurite length (Fig. 1), $\sigma = \sigma_n(T)$ - conductivity.

Properties of individual layers versus temperature were assumed in form

$$\rho_n(T) = \rho_{n0}\left[1 + \alpha_{n\rho}(T - T_0)\right] \qquad (7)$$

$$c_n(T) = c_{n0}\left[1 + \alpha_{nc}(T - T_0)\right] \qquad (8)$$

$$\lambda_n(T) = \lambda_{n0}\left[1 + \alpha_{n\lambda}(T - T_0)\right] \qquad (9)$$

$$\sigma_n(T) = 10^{\frac{a_{\sigma n}}{T} + b_n} \qquad (10)$$

The equation (2) with conditions (3) - (5) was solved within finite difference method in the Crank-Nicolson scheme. The variations of material properties and the place of movable boundary were taken into account by iteration method.

3 Results of calculations

The computations were made for the values of the parameters in the relations from (7) to (10) given in **Fig. 2.**

Because in the literature there are large differences concerning qualitative and quantitative changes of the fulgurite silicates properties versus temperature in the calculation we assumed some averaged magnitudes taken form sources [6,7,9] (Fig. 2). Moreover the properties were linearised by sections according to (7) ÷ (10). By higher temperature than shows in Fig. 2 there is absolute lack of information about above properties. In this case variation of those properties were assumed to be agreed experimental and analytical results. Additionally a continuity of property changes temperature were taken into account.

As it was mentioned earlier the calculations rather are of qualitative character and tend to demonstrate approximated evaluation of several parameters of the post-arc fuse. Having got the measurement results, described in the section 2, concerning the temperature profile in the distance R_s (Fig. 1b) to the fulgurite and the fulgurite resistance over the 0.5 s of post-arc period the following range of analytical investigations was assumed:

- more precise determination of the initial temperature distribution (3) and of the thickness of individual layer using an iteration;
- determination of the temperature distribution over the period under considerations and, on this base, more precise determination of phenomena deciding on changes of the post-arc resistance;
- preliminary evaluation of the fulgurite conductivity versus temperature.

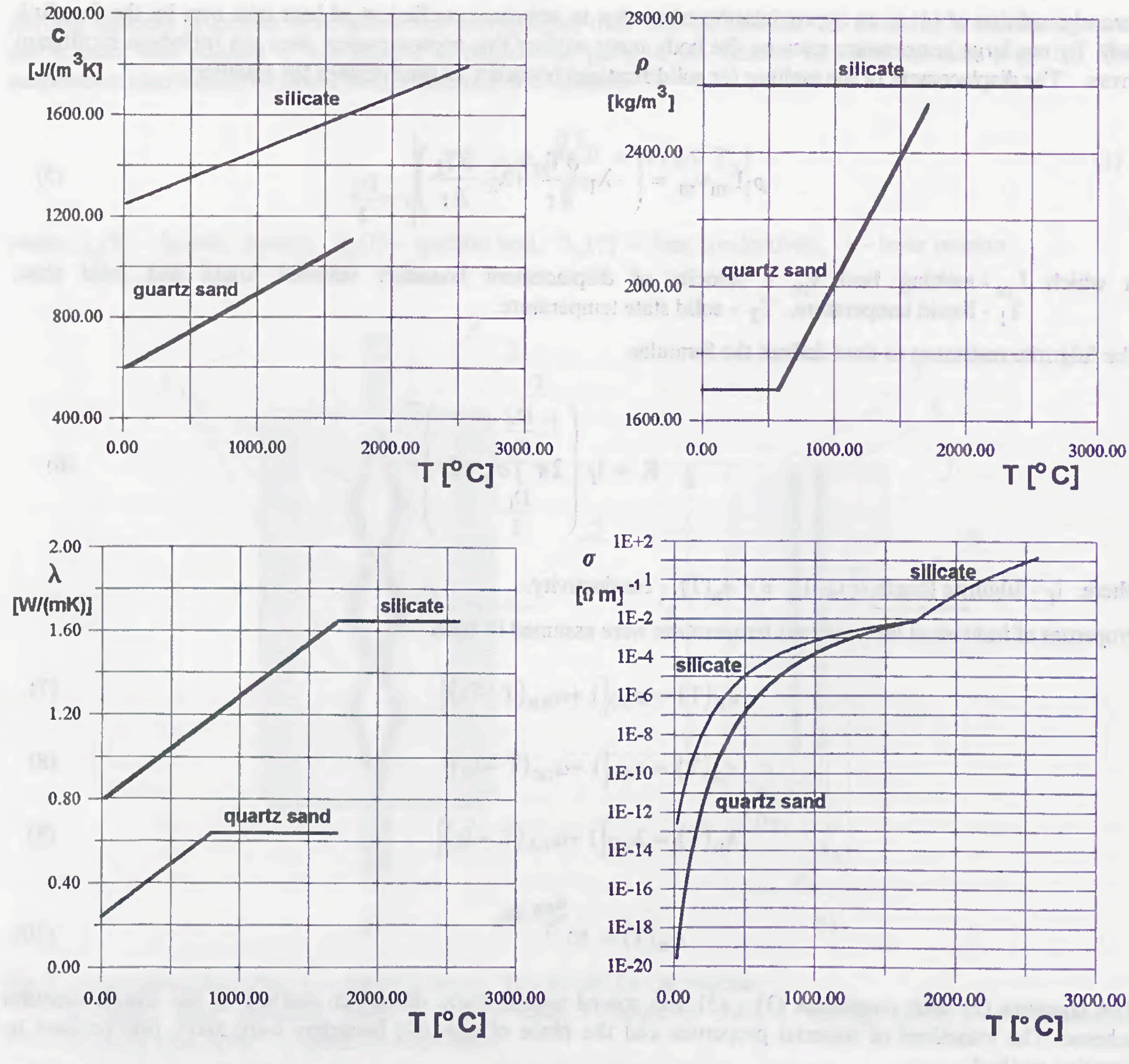


Fig. 2 Properties of quartz sand and silicate versus temperature

Exemplary results of calculations are presented on Figs. 3 ÷ 6.

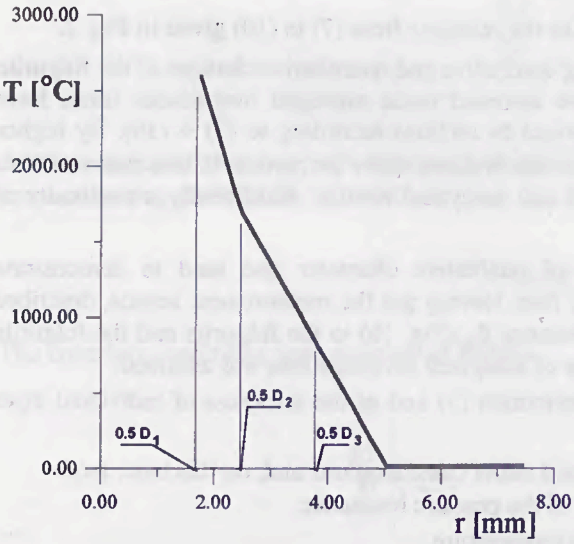


Fig. 3 Calculation of initial temperature distribution along fulgurite radius

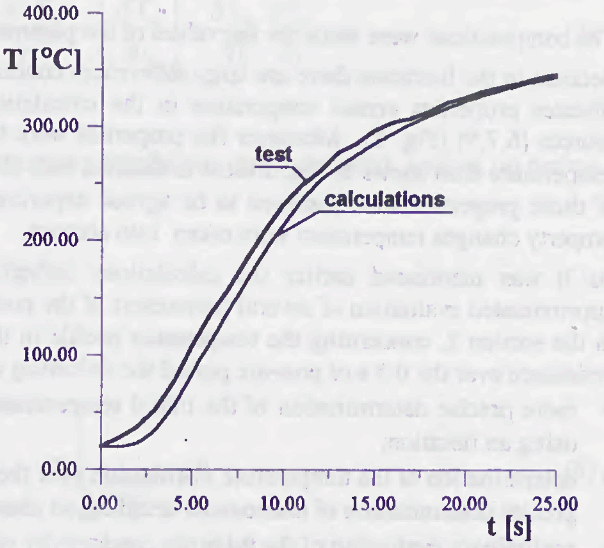


Fig. 4 Relationship temperature on time for distance R_S = 8.25 mm (Fig.1b)

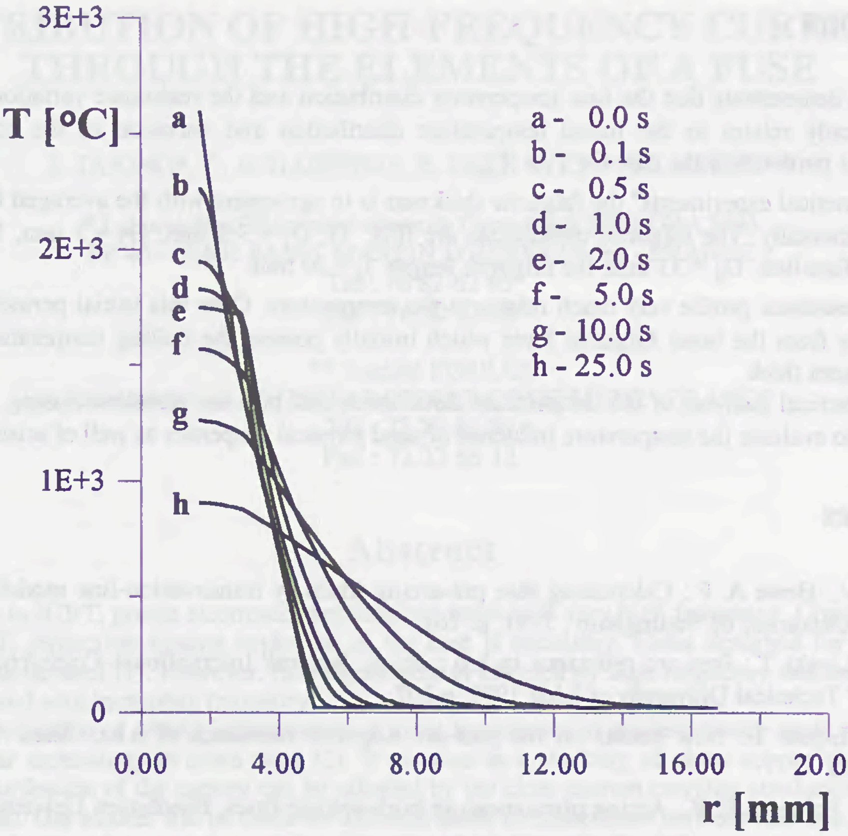
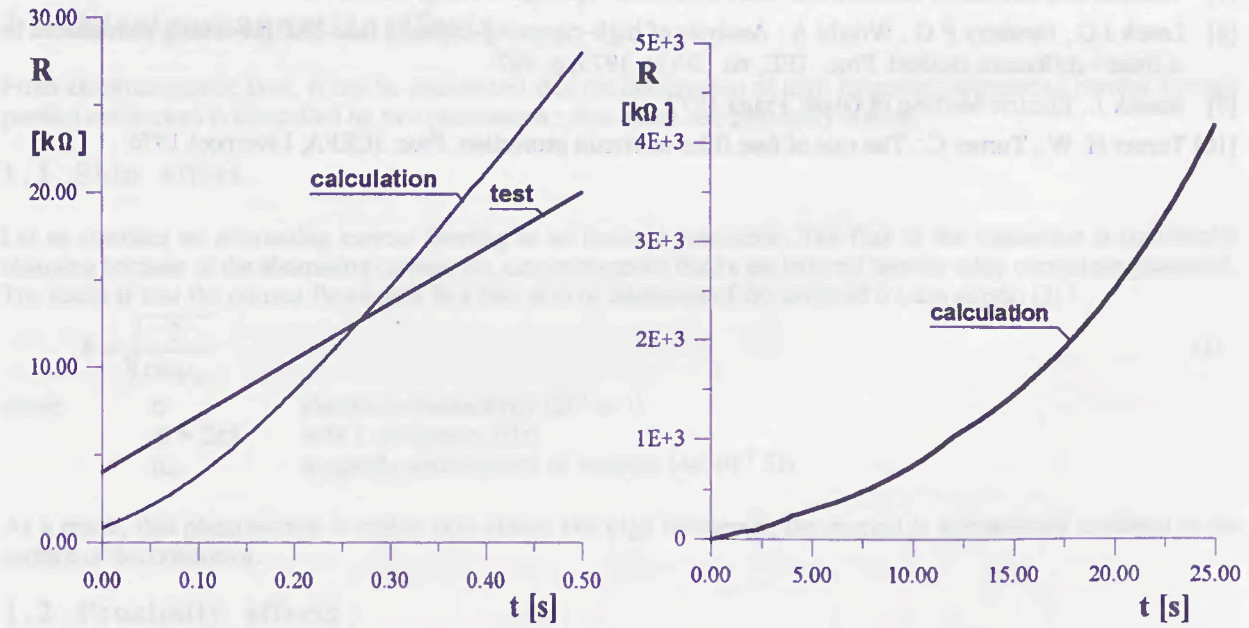


Fig. 5 Temperature distribution versus radius. Parameter is the time instants



a)

b)

Fig. 6 Profiles of resistance of fulgurite versus time: a) t = 0 ÷ 0.5 s, b) t = 0 ÷ 25 s

5 Conclusions

- The calculation demonstrate that the fuse temperature distribution and the resistance variations during post-arc period dramatically relates to the initial temperature distribution and variation of the conductivity versus temperature. It is particularly the case for $T \geq T_m$.
- Defined by "numerical experiments" the fulgurite thickness is in agreement with the averaged fulgurite thickness obtained experimentally. The fulgurite dimensions are (Fig. 1): $D_1 = 3.5$ mm, $D_2 = 5$ mm, $D_3 = 7$ mm, inner diameter of the fuse-link $D_4 = 33$ mm, the fulgurite length $l_f = 30$ mm.
- Initial part of resistance profile very much relates to the temperature. Over this initial period should exist very fast heat transfer from the inner fulgurite layer which initially possess the boiling temperature of quartz. This layer is abt. 0.1 mm thick.
- Carried out numerical analyses of the temperature distribution and post-arc resistance, using 1D simple model, makes possible to evaluate the temperature influence of sand physical properties as well of arising silicates.

6 References

[1] Cheim L.A.V., Howe A. F.: Calculating fuse pre-arcing times by transmission-line modelling (TLM). Proc. 4th ICEFA, University of Nottingham , 1991, p. 162

[2] Ćwidak K., Lipski T.: Post-arc resistance in h.b.c. fuses. Seventh International Conference "Switching Arc Phenomena" Technical University of Łódź 1992, p.202

[3] Ćwidak K., Lipski T.: New results on the post-arc fulgurite resistance of h.b.c. fuses. Proc. ICEFA, TU Ilmenau, 1995

[4] Daalder J.E., Schreurs E. F.: Arcing phenomena in high voltage fuses. Eindhoven University of Technology, 1983

[5] Ehrhardt A., Nutch G., Rother W.: Das Verhalten von elektrischen Sicherungen nach Stromnull. Seventh International Conference "Switchng Arc Phenomena" Technical University of Łódź 1992, p.206

[6] Kikoin I. K.: Tables of physical properties (in Russian). Atomizdat, Moskwa 1976

[7] Landolt und Bornstein: Zahlenwerte und Functionen. Springer Verlag, Berlin 1957

[8] Leach J.G., Newbery P.G., Wright A.: Analysis of high-rupturing-capacity fuse-link pre-arcing phenomena by a finite - difference method. Proc. IEE, no 120(9), 1973, p. 987

[9] Stanek J.: Electric Melting of Glass. Praga 1977

[10] Turner H. W., Turner C.: The role of fuse filler in circuit protection. Proc. ICEFA, Liverpool 1976