THERMAL PROCESSES IN SF_6 - FILLED FUSES BELOW THE MINIMUM MELTING CURRENT

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Summary

In conventional sand-filled fuses, heat transfer is predominantly determined by conduction. However, in case of gas-filled fuses, the influence of convection and radiation must be taken into account.
The investigations described aim at calculating the temperature distribution in the fuse and thus determine the minimum melting current using an approximation procedure. The calculated results are compared with measurements on test samples. The comparison shows that the calculation model applied is a suitable one.

1. Introduction

Conventional high voltage fuses in general have a zone of an uncertain arc quenching capability and by this show an uncertain switching performance in the low overcurrent region. A fuse filled with SF_6 overcomes this disadvantage if a quick lengthening of the arc happens and thus a fast recovery of the dielectric strength after current zero can be archieved [1]. In that case extinguishing of the arc can be reached and all currents above the minimum melting current can switched off reliable .

One of the major remaining problems is the exact determination of the minimum melting current, which leads to disintegration of the fuse wire. Therefore, a study might be useful, which aims at its determination by calculating of the relevant temperature field. In order to check the accuracy of these computations, the calculated temperatures are to be compared with measured ones.

2. Minimum Melting Current I_{mm}

During high short-circuit currents heat transfer phenomena are assumed to be negligible. The expected melting time of the fuse wire can be calculated for this adiabatic case from [2]:

$$\int_0^{t_m} J^2 dt = const. \tag{1}$$

where, t_m - melting time
J - current density
t - time

For each fuse exists a current level, at which melting would theoretically commence after an infinite long time. This current, which is important for theoretical considerations, is called the minimum melting current I_{mm}. For currents above the minimum melting current I_{mm}, equ.(1) can be modified to

$$(I-I_{mm})^2 * t = a \tag{2}$$

where, a characterizes the stored heat energy Q_{wire} in the fuse wire. If heat flow from the fuse wire in axial and radial direction becomes more important, which is the case for decreasing currents, one more term must be added for the stored energy in the surroundings Q_{sur}.
Q_{sur} may be assumed according to the empirical equation

$$Q_{sur} = b * t^{1/3} \tag{3}$$

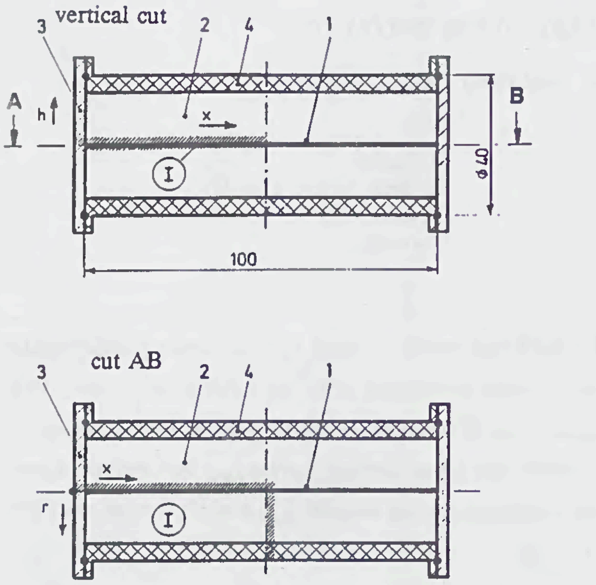
in which b is a constant.
Thus, equ. (2) may be expanded by the term given by equ.(3) to

$$(I-I_{mm})^2 * t = a + b * t^{1/3} \tag{4}$$

In principle, the unknown parameters a, b and I_{mm} can be evaluated from the time-current characteristic by at least three independent experiments [2]. However, the evaluation of the minimum melting current I_{mm} as defined above is associated with a fairly high uncertainty.

3. Test Arrangement

Fig. 1 shows the subject of investigations in horizontal position as used for measurements and calculations. The fuse wire (1) is placed concentric in the insulating tube (4), which is closed by metal end caps (3) and filled with SF_6. Due to the movement of the gas, upper parts of the model are at other temperatures than lower parts at the same distance of the wire. This was confirmed by measurements.



1 - fuse wire
2 - SF_6 (p_{abs} = 4 bar)
3 - metal end caps
4 - PMMA tube
(I) - quarter, to which calculations are restricted

Fig. 1: Test Arrangement

Because these differences of temperature between upper and lower parts are smaller than 60 ^{0}C, it is useful to restrict measurements and calculations to the plain section with the height h=0, marked by "I" in Fig. 1. The influence of the thermo couples on the gas flow is neglected. Thus axial and radial symmetry is assumed and further considerations are restricted to the quarter marked by "I".

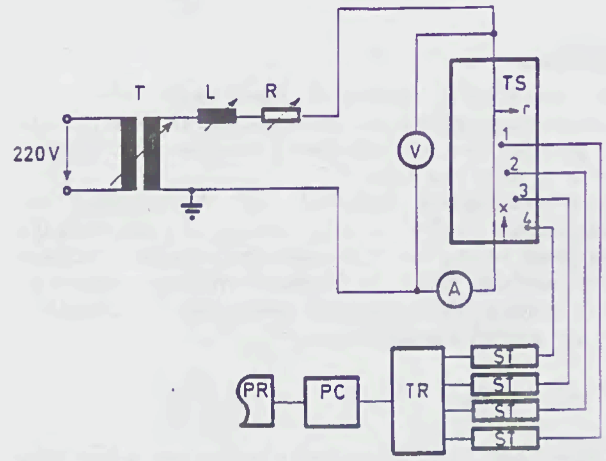
The test circuit and the measuring equipment is shown in Fig. 2. The specimen can be stressed by currents up to 60 A. The fuse wire and its surroundings is heated up by the current. The actual temperatures in the surroundings are measured with Ni-NiCr thermo couples, which are usuable up to 1000 ^{0}C. Table 1 gives their axial and radial horizontal positions.

Table 1: Positions of the thermo couples in the test specimen

number of thermo couples	axial position x	radial position r
1	42 mm	2 mm
2	22 mm	3 mm
3	41 mm	6 mm
4	22 mm	14 mm

The signals of the thermo couples are converted in a special signal transformer (ST) (Typ AD594, Manufacterer: Analog Devices) to a voltage proportional to the temperature. This voltage is led to a transient recorder (TR). The personal computer (PC) stores the measuring results for further usage.

It seems to be unfavourable to measure the temperature of



T - transformer
L - variable inductance
R - variable resistance
TS - test specimen
TR - transient recorder
PC - personal computer
PR - printer
1,2,3,4 - number of the thermo couples (tc)
x,r - position of the thermo couples (tc)
ST - signal transformer

Fig. 2: Test circuit and Measuring Arrangement

the fuse wire with the help of a thermo couple, since it could cause an undesirable cooling of the relevant wire section. Therefore a different way to evaluate the wire temperature was used. Since with increasing temperature of the fuse wire the resistance and consequently the voltage drop at the fuse increases, too, this voltage drop is a measure for the wire temperature, provided that the current is kept constant. The measuring accuracy of the voltage drop is less than ∓5 mV.

4. Calculation Model

Heat is transferred by three basic modes: conduction, convection and radiation. The physical mechanisms and laws of heat transfer are different for each of these three modes. The influence of each mode on heat transfer depends on the physical properties of the materials, the geometry and the temperature gradients.

Heat transfer can be described with the help of a system of differential equations. But, for most of the heat transfer problems, which are of practical importance, an analytical solution does not exist [3,4]. Therefore it is necessary to find other possibilities for solution. One of these could be the theory of geometric similarity [5], from which the relevant thermal processes can be deducated as depending on "dimensionsless numbers". If these numbers are known, a known solution may be transferred to similar problems.

The desired "dimensionsless numbers" are defined as follows:

Grashof number $$Gr = \beta * \frac{g * l^3}{\nu^2} * \Delta\vartheta \quad (5)$$

Prandtl number $$Pr = \frac{\eta * c_p}{\lambda} \quad (6)$$

Nusselt number $$Nu = \alpha * \frac{l}{\lambda} \quad (7)$$

where is

- β = coefficient of thermal expansion
- g = acceleration due to gravity
- l = significant length
- ν = kinematic viscosity
- ϑ = temperature
- η = dynamic viscosity
- c_p = specific heat at constant pressure
- λ = thermal conductivity
- α = heat transfer coefficient

The **Grashof number** can be interpreted as the ratio of fluid flow inertia forces to viscous forces [6].

The **Prandtl number** compares the kinematic viscosity for pulse transport by friction with the energy transport by conduction [4].

The **Nusselt number** can be interpreted physically as the ratio of the temperature gradient in the fluid in contact with the surface to a reference temperature gradient [6]. However, in the following Nu was not used, since α is unknown for this relevant problem.

With the help of these numbers, the different mechanisms of leading away the heat generated in the fuse wire can be investigated.

The area of the quarter section of the fuse model is subdivided in segments with an area of 1 mm². The generated power per increment of the fuse wire dP is

$$dP = I^2 * \rho(\vartheta) * \frac{dx}{A} \quad (8)$$

where

- I - current
- ρ - specific resistance
- ϑ - temperature
- dx - incremental length of the wire
- A - area of cross section of the wire

For all currents below the minimum melting current I_{mm}, this power has to be carried off to the surroundings. Thus the considerations can be restricted to the steady state [7].

In the gas, heat is transferred in radial direction by conduction, convection and radiation. Due to the cylindrical form of the fuse, the heat transported by **conduction in radial direction Q_{lr}** can be written as:

$$Q_{lr} = \frac{2\pi * \lambda_{SF_6} * l}{\ln\frac{r_a}{r_i}} * \Delta\vartheta \quad (9)$$

- λ_{SF6} - thermal conductivity of SF_6
- l - length of the fuse wire
- r_a - outside radius of the incremental layer
- r_i - inner radius of the incremental layer
- $\Delta\vartheta$ - temperature difference between r_a and r_i

The influence of convection Q_c depends on the type of flow. In the vicinity of the wire, a boundary layer exists with a laminar flow. Inside this boundary layer, no heat transfer by convection, but only by conduction, exists. Outside this section, the influence of convection can be taken into account by an "effective" thermal conductivity λ_{eff}. Since λ_{eff} is a function of the product of the Grashof and the Prandtl number, it can be written [3]:

$10^0 < Gr*Pr < 10^3$

$$\frac{\lambda_{eff}}{\lambda} = 1 \quad (10)$$

$10^3 < Gr*Pr < 10^6$

$$\frac{\lambda_{eff}}{\lambda} = 0{,}105 * (Gr * Pr)^{0,3} \quad (11)$$

$10^6 < Gr*Pr < 10^{10}$

$$\frac{\lambda_{eff}}{\lambda} = 0{,}4 * (Gr * Pr)^{0,2} \quad (12)$$

Equ. (12) signifies that the total heat transfer is considered as resulting only from conduction. The decrease of λ_{eff} for large values of the argument (Gr*Pr) in equ. (12) can be explained with reciprocal disturbances between streams of rising and falling gas.

Using the idea that an "effective" thermal conductivity λ_{eff} exists, which takes into account convection effects, thermal resistances can be established to figure the influence of convection. Thus, the relevant heat Q_c **can be calculated by replacing** λ_{SF6} **in equ. (9) by the term** $(\lambda_{eff} - \lambda_{SF6})$.

Additional to conduction and convection, heat is transported by **radiation** Q_{rad} as given by [3]:

$$Q_{rad} = \varepsilon_{Ag}(\vartheta) * A * C * \left\{ \left(\frac{\vartheta_{Ag}}{100} \right)^4 - \left(\frac{\vartheta_W}{100} \right)^4 \right\} \qquad (13)$$

ε_{Ag} - emission coefficient of silver
A - surface area of the fuse wire
C - radiation number
ϑ_{Ag} - temperature of the fuse wire
ϑ_W - temperature of the wall

In solid materials, such as fuse wire and fuse wall, heat is transferred only by conduction. Heat is transferred from the outer surface of the fuse to the surroundings by conduction, convection and radiation.

Heat is transferred in **axial direction only by conduction** Q_{la}.

$$Q_{la} = \lambda_m * \frac{\pi * (r_a^2 - r_i^2)}{\Delta l} * \Delta\vartheta \qquad (14)$$

λ_m - thermal conductivity of the medium
Δl - incremental length
r_a - outside radius of the incremental layer
r_i - inner radius of the incremental layer
$\Delta\vartheta$ - difference of temperature along Δl

Based on the described considerations, a thermal equivalent circuit was developed. Thermal resistances are calculated taking into account the different relevant heat transfer mechanisms. This network has thermal current sources in each increment which correspond to the heat generated. Calculation of the temperature is reduced to a calculation of the network's potentials.

From these potentials, the temperatures in the fuse are known. Knowing the melting temperature of the fuse wire, the minimum melting current is calculatable. The knowledge of the temperatures and the resistances enable to analyse the contribution of the different mechanisms of heat transfer.

5. Results

As shown by Fig. 3 the temperatures at different test points, as given in Table 1, do not further increase after a time of 90 minutes which signigicies that the "steady state" is reached. In that state the measured values can be compared

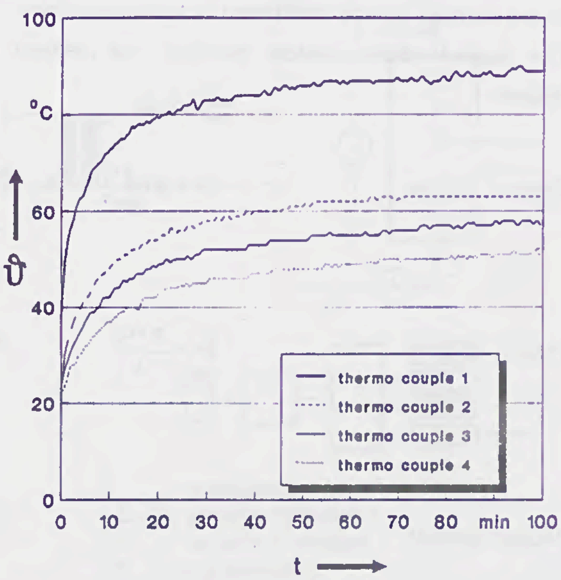
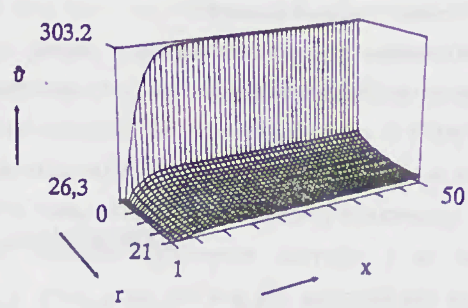


Fig. 3: Measured temperatures as a function of time at the positions of the thermo couples number 1-4
Parameters: I = 14.5 A
fuse wire diameter 0.4 mm

with those, which we calculated. Fig. 4 shows a calculated temperature distribution over the quarter of the specimen as marked in Fig. 1. Noticeable are the very strong temperature gradients in radial direction and in axial direction close to the caps. At 10 mm from the caps the temperature of the



x - control variable for the axial position
r - control variable for the radial position
ϑ - temperature

Fig. 4: Calculated temperature distribution in a quarter of the cross section of the test body.
Parameters: I = 11.04 A
fuse wire diameter 0.35 mm

fuse wire has reached 95 % of the maximum value (303 °C). The temperature in the SF_6-atmosphere is in the middle relatively low (about 50 °C).

For the same conditions the temperatures were measured with the equipment according to Fig. 2. Fig. 5 shows the comparison between the calculated and the measured values in the four positions of the thermo couples. The deviations are smaller than 20%. This might be due to the applied simplifications.

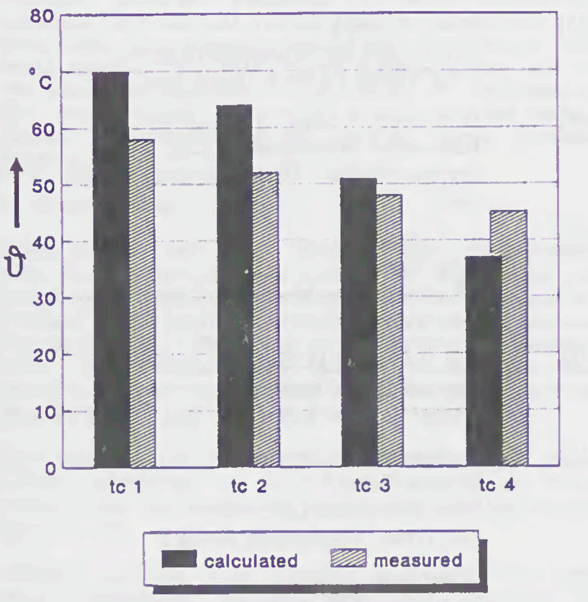


Fig. 5: Comparison between measured and calculated temperatures at the positions of the thermo couples (tc).
Parameters: I = 11.04 A
fuse wire diameter 0.35 mm

Fig. 6 shows a comparison of the measured voltage across the fuse and the calculated voltage drop calculated with the described model. These voltages differ essentially.

By dividing the voltage difference by the relevant current, a constant contact resistance was obtained, which was 54 mΩ in the case of Fig. 6. This resistance is given by the clip positions of the wire. Considering these contact voltage drops, the deviations between calculated and measured voltage are smaller than 60 mV, which is a fairly good agreement.

Furthermore, Fig. 6 shows the calculated maximum fuse wire temperature. At 960 °C [8], the melting temperature is reached. The corresponding current value is 15.8 A, while the minimum melting current I_{mm} as determined in chapter 2 is 15.0 A. Measured and calculated values of the minimum melting current I_{mm} are in a good agreement.

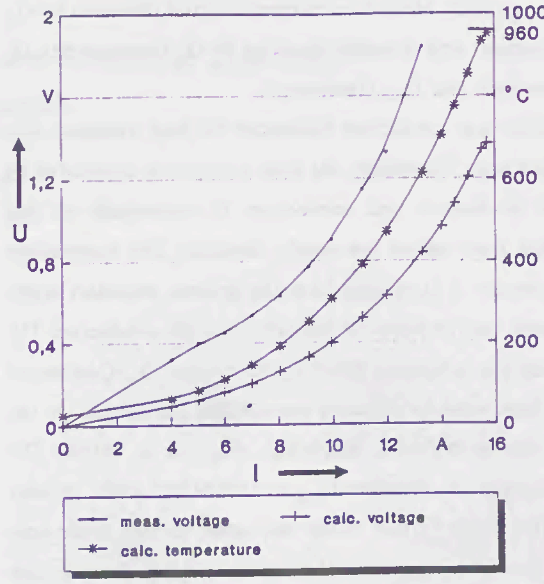


Fig. 6: Comparison between calculated maximum fuse wire temperature, calculated and measured voltage drop across the fuse wire as a function of current for a fuse wire diameter of 0.32 mm.

The different mechanisms of transporting the heat from one wire element to the neighbouring is investigated. The wire diameter here is 0.32 mm and the current 15.6 A. Fig. 7

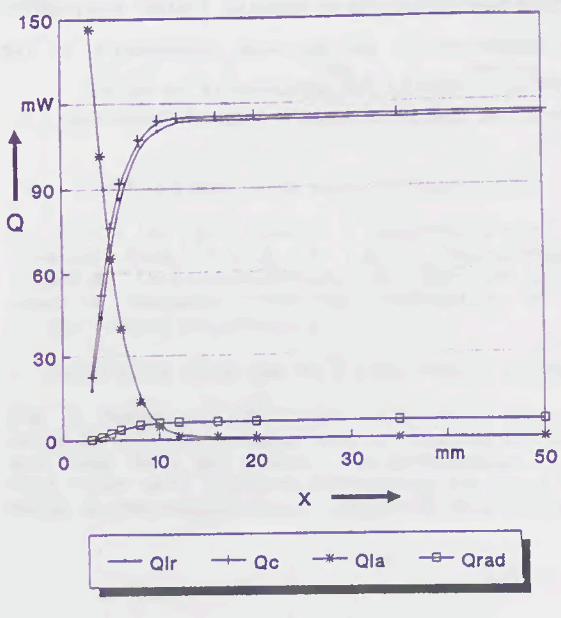


Fig. 7: Transported heat portions per wire increment by different mechanisms such as radial conduction Q_{lr}, convection Q_c, axial conduction Q_{la} and radiation Q_{rad}.
Parameters: I = 15,6 A
fuse wire diameter 0.32 A

gives the result. Heat is transferred in axial direction by Q_{la} (conduction) and in radial direction by Q_{lr} (conduction), Q_c (convection) and Q_{rad} (radiation).

The axial heat conduction influences the heat transport only near the caps. Thereafter, the heat transport is dominated by radial conduction and convection. Coincidentally in this example their values are nearly identical. The surprisingly high portion of Q_{lr} results from the laminar boundary layer, in which heat transfer is possible only by conduction [3]. Outside this boundary layer, Q_c dominates Q_{lr}. Combining these conditions by applying two parallel resistances for the first segment in the SF_6-gas, a high value for Q_{lr} results. The contribution of radiation Q_{rad} to the heat transfer is only 5%. This might be due to the very small surface of the fuse wire. Thus, the important mechanisms in radial direction are conduction and convection.

6. Conclusions

Approximate calculations of the heat transferred from the fuse wire to the surroundings with help of a model as described in chapter 4 enable to calculate the temperature distribution in a fuse filled with SF_6.

Based on the calculated wire temperatures, the minimum melting current can be determined. Furthermore the heat transfer mechanisms can be analysed. Further investigation are under way to get improved informations on the permissible limits for the application of the model.

7. References

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