A COMPARISON OF THE COMPUTER MODELLING OF ELECTRIC FUSE ARCING AND THEIR REAL-LIFE PERFORMANCE

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Abstract

Using optical fibroscopy the burnback of electric fuse elements was monitored. Alongside this a computer program was developed to model the burnback process. The rate of burnback is dependent on the percentage of eroded fuse element material that is vaporised. By comparing the experimental and computational results it was established that approximately 10 per cent of the eroded element material was vaporised whilst the rest flowed away as liquid into the filler interstices. With this data the accuracy of fuse arc models should be improved.

1. Introduction

The operation of fuses may be divided into two parts, namely a pre-arcing period during which elements are heated, melted and then break up, and an arcing period which continues until current flow is interrupted.

Behaviour during the pre-arcing period is well understood and can be modelled accurately using numerical techniques [1,2]. Behaviour during arcing is still not fully understood and continues to attract the interest of researchers, as manufacturers seek more accurate models of the arcing period. Currently, every time a new fuse is designed manufacturers must do experimental testing. Much of this expensive work could be eliminated if accurate numerical models were available. Existing models which are based either on empirical methods or energy balances are insufficiently accurate to be reliable because of the large number of interactive parameters that are associated with the arcing process [3]. This paper describes work, which was designed to try to relate two of these parameters, burnback rate and the proportion of element material which is vaporised.

Wright and Beaumont [3] examined microscopically the fulgurite which surrounds an operated fuse element and discovered that during arcing some of the element material flowed out in liquid form into the spaces among the filler granules, whilst other element material was vaporised, forced out into the interstices by the pressure of the arc and deposited finely on the filler material. As the amount of energy required to melt a particular volume of material is far less than that necessary to vaporise the same volume, the percentage of eroded element material that is vaporised will have a significant effect on the fuse burnback rate and hence its operating characteristic. This work, which was designed to ascertain this percentage, had two parts. The first was experimental to measure the burnback rate and the second was computational.

2. Burnback experiments

This work has been described previously [4] but for the convenience of the reader the salient points are repeated here.

Fuselinks were constructed with a narrow slot cut longitudinally in the fusebody perpendicular to the plane of element. Five optical fibres were inserted so that the first lay approximately over the restriction and the remainder formed a line with each touching its neighbour as shown in Fig. 1. Each fuse was then filled with sand to normal packing density.

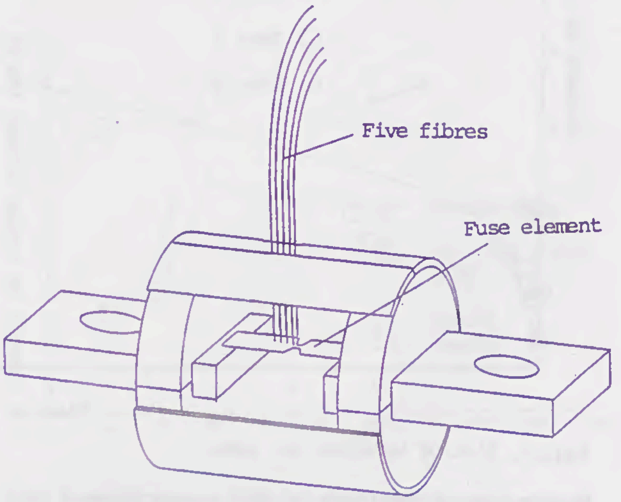

Fig. 1 Fuse design for burnback measurement.

When each fuse was operated, its arc length increased and light from the arc appeared first from the fibre over the centre of the restriction and then from the others successively. Fig. 2 shows the light outputs during one test.

The traces fall when light is emitted from the fibres. The top trace is the one from the fibre over the restriction in the element, the lower traces being in the order of the fibres. From these results it was possible to plot graphs of burnback versus time. Fig. 3 shows the results from three tests.

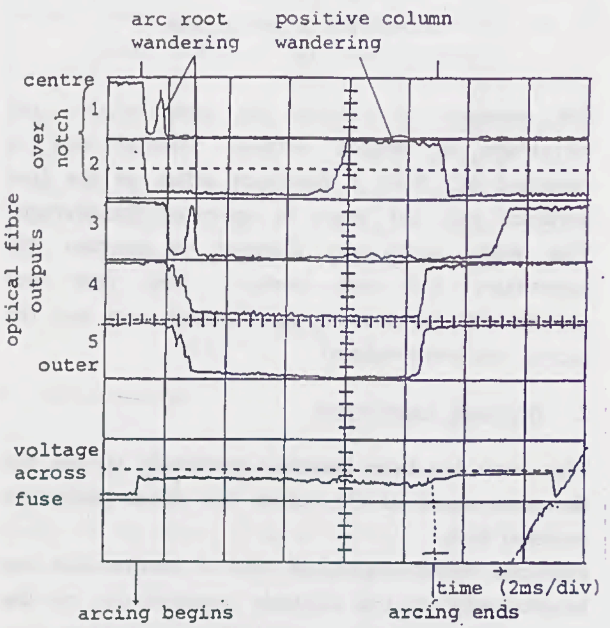

Fig. 2 Multi-trace plot of burnback (Test 1).

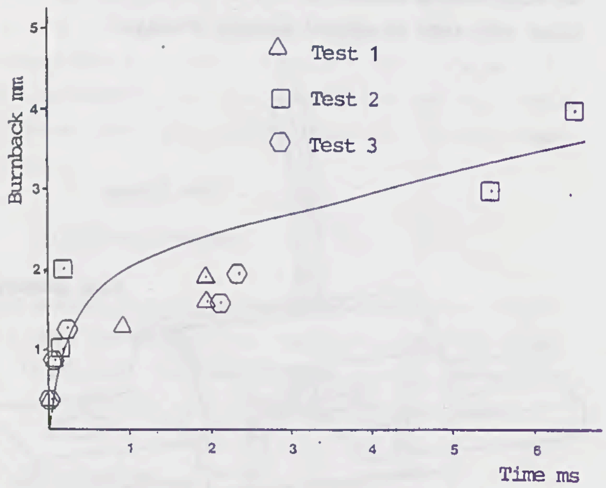

Fig. 3 Plot of burnback vs. time.

Examination of the traces of light output showed that sudden diminutions in light intensity occur for periods of up to 3 ms, indicating that the arc wanders [5]. Signals from the outer fibres cease abruptly about 0.5 ms before the drop in arc voltage, normally associated with the end of arcing. Light continued to be emitted from the inner fibres after the end of arcing probably due to incandescence of the fulgurite.

3. Numerical modelling

The numerical model was based entirely on the concept of energy balances. No consideration was given to the processes taking place within the arc and it was assumed that the arc itself had no intrinsic energy.

When the duration of electric fuse arcing is only a few milliseconds then the arcing process may be considered to be essentially adiabatic, so that negligible heat is transmitted beyond the immediate layer of the filter surrounding the element. Because of this, it was possible to construct a numerical model based upon the electrical energy supplied acting solely upon the surface layer of the filler.

3.1 Fuse model

The fuse was considered as a section with width equal to the width of the element and with infinite height and length as illustrated in Fig. 4. The element was situated at the centre and was represented by a layer with a thickness equal to that of the element and with the physical attributes of the element material. The rest of the model which represents the filler was divided with layers Δz thick.

The model was divided longitudally into segments Δx long.

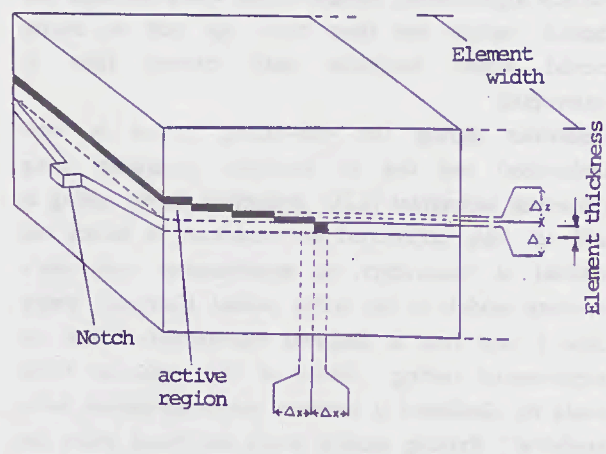

Fig. 4 Fuse element showing modelling sub-volumes.

The heat capacity of the filler and the element material were derived for the temperature ranges 293K to their respective melting points, since in the physical tests the fuses had equilibrated with room temperature and were not pre-heated. The heat capacity of the filler and the element were derived using the expression

$$Cp = a + b \times 10^{-3}T + c \times 10^{-6}T^2 + d \times 10^5/T^2$$

where a, b, c and d are constants and T is the temperature [6].

The constants have different values for the solid and liquid phases. In order to obtain values for the heat capacity of the materials, values were calculated in 10K intervals up to their melting point. The values so derived were integrated to provide a lumped value for heat capacity up to the material's change of state. The latent heat of melting and the latent heat of vaporisation were added to the integrated value to provide the total heat to vaporise unit mass of material. In the case of the filler vaporisation does not occur since silica decomposes directly from its liquid phase at 2523K. The decomposition requires an amount of energy equal to the heat of formation of silica from its elements at that temperature, and so this value was used in place of the latent heat of vaporisation.

3.2 Energy considerations

The total energy supplied to the fuselink in the time interval Δt was equal to $i\ v\ \Delta t$

where i = instantaneous current

v = instantaneous voltage across the fuse.

As the system was assumed to be adiabatic all of this energy was used to:

i) heat up and erode the element, and

ii) heat up and decompose the filler material adjacent to the surface of the element.

The energy required to erode the element has been quoted by a number of authors [7-9] as being equal to $i\ v_{ar}\ \Delta t$

where v_{ar} = arc root voltage.

For simplicity some authors have ignored the heat conduction from the arc along the element. However, as some of this energy must be dissipated in raising the temperature of the element, this effect was considered here.

The rest of the supplied energy was available for heating and decomposing the filler material surrounding the element.

3.3 Modelling implementation

The model was initialised at the moment the restriction was broken, and then progressed in 1 μs time steps.

At each time step, Δt, the total energy supplied to the fuse during that interval was calculated. To do this the instantaneous current, i, and voltage, v, measurements made during the burnback experiments were supplied as data.

As the percentage of eroded element material that is vaporised was unknown an arbitrary value was chosen initially. Then using the concept of arc root voltage the energy supplied to the element subvolume adjacent to the break in the element was calculated, assuming that the arc root voltage was 14V. After determining the proportion of this energy, that is necessary to heat the element ends [5], the remainder was added to the total stored energy in the element subvolume. When the total energy exceeded the amount required to vaporise the chosen percentage of element material in the subvolume, this section was set aside and the excess energy was used to start heating the next subvolume.

The energy supplied during each time step to the surface of each subvolume of filler was then determined and added to the previous value for that subvolume. When sufficient energy had been provided to decompose the subvolume that segment was discarded and the excess energy was used to start heating the next layer.

Iterations continued until the current reached zero. The procedure was then repeated for other percentages of eroded element material.

3.4 Results

The computations gave consistently high rates of element erosion when the heating of the element was ignored (as illustrated in Fig. 5, graph labelled "arc root volts only"). However, reasonable correlation with the experimental results was achieved when the heating of the element ends was included and it was assumed that 10% of the eroded element material was vaporised and 90% was forced away from the arc as liquid. This is the "normalised" graph in Fig. 5.

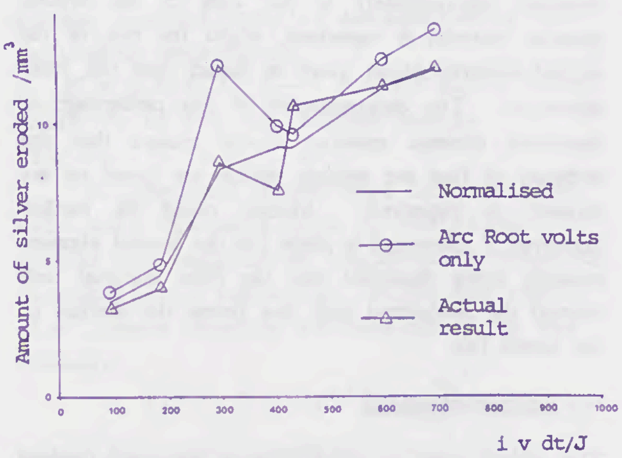

Fig. 5 Amount of silver eroded vs. supplied energy (computed and practical results)

Fig. 6 shows the same comparison in the form of a graph of burnback length versus time. Again there is reasonable correlation. The error at short elapsed times was due to simplified modelling of the element restriction.

A number of authors have noticed variations in the burnback rate when elements are preheated. To examine whether this effect could be demonstrated using the computer program the initial temperature of the element was raised, and it was found that temperature rises as small as 25K had a marked effect on burnback rate.

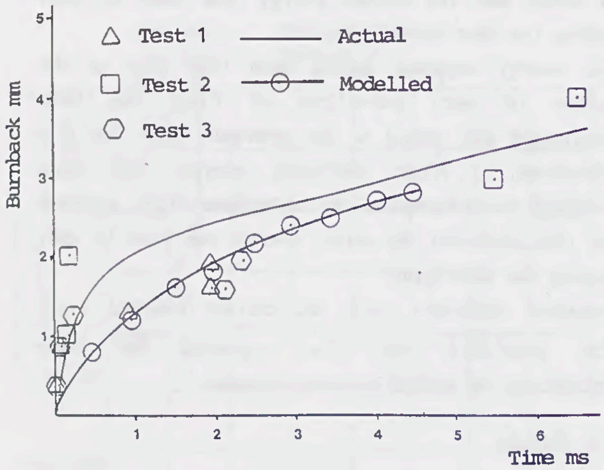

Fig. 6 Burnback vs. time.
(Computed and practical results)

4. Conclusions

The rate of fuse element burnback has been measured using optical fibres. Using these results and a simple numerical model of the erosion mechanism, it has been established that providing the arcing process is adiabatic approximately 10 per cent of the eroded element material is vaporised, whilst the rest of the eroded material flows away as liquid into the filler interstices. The determination of this percentage of vaporised element material should ensure that the accuracy of fuse arc models, which are based on arc physics, is improved. Models could be further improved if allowance is made for the eroded element material being dispersed into the filler material well beyond the isothermal wall that forms the surface of the lumen [10].

5. Acknowledgements

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