ANSYS Model for the Prediction of the Pre-Arcing Period

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Abstract— **A transient thermal-electric finite element method (FEM) model is developed to simulate the heating processes of a fuse element to predict the behavior until the boiling point is reached (pre-arcing period). In this contribution, 2D and 3D models are compared with respect to result accuracy based on published modeling and experimental results. Accurate temperature dependent properties for different fuse element materials - electrical resistivity, thermal conductivity, and enthalpy - based on literature data are used in this model. It is shown, that while the 2D model is very efficient for high short-circuit current loads, the 3D model must be used for overcurrent loads. In addition to the basic model, a simplified algorithm for diffusion processes related to the "M-effect" operation during a low overcurrent load has been implemented. Output from our model is in good agreement with measured results and shows, that nowadays computational power allows to use even desktop computers to do modeling effectively and thus speed up the development process.**

***Keywords*—FEM, M-effect, modeling, pre-arcing phase.**

I. Introduction

Electric fuses as the oldest protection devices for electric circuits have not changed their main concept significantly in recent years. There are still fuse-links with weak-spots (notches) and with M-effect spots. However, new applications in the last decade – mainly the shift towards DC applications, electric vehicles or DC microgrids for example – have forced manufactures to develop specialized DC fuses. During such a development a huge number of trial-and-error tests must be done, which increases the time to development of the final product.

One way to reduce development time is to use numerical modeling instead of several trial-and-error tests. The first attempts to model fuse operation were made during 1980s and early 1990s [1]. Since that time, together with increase of computational power, more advanced models have been developed. Nowadays we can model simple pre-arcing phenomena on desktop computers. In fuse operation modeling we distinguish two basic models: pre-arcing [4] and arcing [5]. While the first one covers mainly electro-thermal physics, i.e. Joule heating and heat transfer, the latter includes magnetohydrodynamics of the arc, electromagnetic radiation, interaction of the arc with sand filling etc., which indicates high complexity of arc modeling. In this article, we focus on modeling the pre-arcing phase.

One of the most important data of interest for engineers or technicians dealing with electrical fuse applications during the pre-arcing phase is the time-current characteristic (TCC), which is essentially a log-log plot of the melting time of the fuse element vs. the applied rated electric current (RMS). The currents of interest can range anywhere between small overloads (1.3x rated current) and short circuits (~20x rated current). The TCC is the first requirement for the users/customers of a given fuse, which needs to be provided by the manufacturer. In practice, generating this TCC for a given fuse design is an extremely laborious process, in which test engineers perform approximately 3 tests per current decade and then utilize time-consuming interpolation techniques to determine the melting time for intermediate current values. The experimental tests require pre-planned laboratory time, material resources and finally, experienced personnel to manually generate TCCs for different fuse designs. Specifically, a significant test time and cost reduction is possible if the TCCs can be generated computationally for complex fuse designs.

As we have three main ranges of fuse operation, we can also have three main pre-arcing modeling scenarios, which are: i) short-circuit current operation with current $I > 10 \cdot Ir$, ii) high overload current operation with approximately $4 \cdot Ir < I < 10 \cdot Ir$, and iii) low overload current operation $Ir < I < 4 \cdot Ir$, where Ir is the rated current. During i), the Joule heating increases so rapidly, that there is negligible heat transfer to the sand and we can consider this case as adiabatic in the model. During ii), we need to consider heat transfer to the sand and thus need to use a 3D model. During iii), the current is so small that it can take hours to heat the fuse above melting temperature of the fuse-link material. For these cases, the so-called M-effect is utilized, where a tin layer is added onto the fuse-link. When the tin melts, copper or silver start to diffuse into liquid tin. This diffusion makes the fuse-link thinner and leads to creation of more resistive alloys, thereby increasing Joule heating and subsequently, the diffusion speed. To model this phenomenon, there is a need to implement such a diffusion process.

II. Model Description

Owing to the ease of application and features of the ANSYS software regarding design optimization, we have utilized the transient thermal-electric simulation package of ANSYS to calculate the melting time for a prescribed current profile, with and without M-effect. In the model, zero (grounded) voltage is defined on one terminal and current is defined on second terminal as electrical boundary conditions. Thermal boundary conditions change with the regime of operation. For short circuit tests, we can neglect heat transfer from fuse-link into the surroundings and we can set fully adiabatic boundaries. For overload cases, we must account for heat transfer through convection and radiation at the boundaries. We can set either fixed temperature to the terminals of fuse-link or we can model cable connections which increases results accuracy but also increases the computational time. The simulation is stopped when the vaporization temperature is reached anywhere within the computation domain.

For small overload current including the M-effect, we have implemented simplified diffusion algorithm [2] with small modifications to increase accuracy. This algorithm is implemented in the ANSYS Workbench [7] by using APDL command snippets and it is evaluated at the end of every load step. During each time step, the temperature under the tin layer is evaluated and from the temperature and concentration at the previous time step, we calculate diffusion speed followed by new diffusion depth. From the new diffusion depth, material parameters – namely electrical resistivity and thermal conductivity – are calculated and updated in the model.

III. Results

The first step towards model development for optimizing fuse design is to analyze simplified geometries for which experimental TCC test data is available, and henceforth, compare the numerical simulation results for the pre-arcing time with the test data. For this purpose, we have numerically determined the pre-arcing time for the 3D fuse element geometry, subjected to a stipulated AC profile, considered by Rochette *et al.* (named "Test 3" in figure 12 [5]). Similar to [5], we define the pre-arcing time to include both melting and vaporization. The accuracy of the thermo-physical properties data, especially their variations with temperature, are extremely important for an accurate prediction of the pre-arcing time. These data for silver were directly taken from [5]. The experimental pre-arcing was observed to be 16.5*ms*, while the numerical value reported by Rochette *et al.* [5] was 22*ms*. Using the fully adiabatic assumption in our simulations, we have determined the pre-arcing time to be approximately 16.3*ms*.

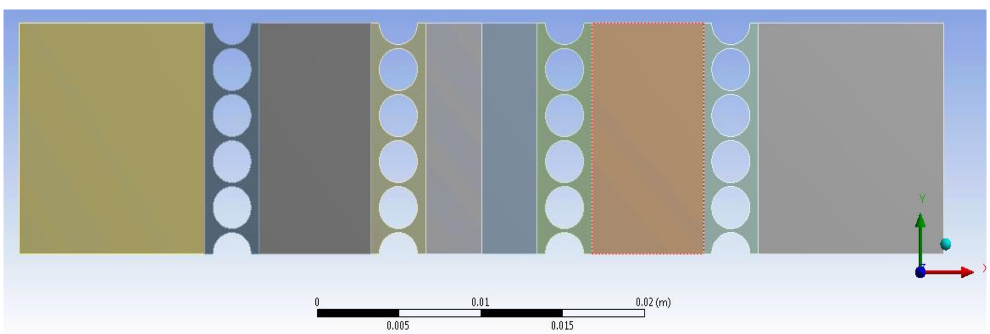

Figure 1. 3D test geometry, subjected to a DC high over-current load (5x rated current).

Subsequently, we have considered an internal test element made of copper, as shown in figure 1 and subjected it to a DC high-overload current of magnitude 545*A*, which is roughly five times the rated current and with a time constant of 4.7*ms*. The experimental pre-arcing time was observed to be 36.0*ms*, while the calculated pre-arcing time including the heat transfer to sand, as shown in figure 2, is approximately 36.5*ms*. The arrows clearly mark the phase changes, namely melting and vaporization. The fully adiabatic assumption resulted in a pre-arcing time of approximately 25.5*ms*, which highlights the importance of considering the heat transfer to sand for short- to high-overload currents.

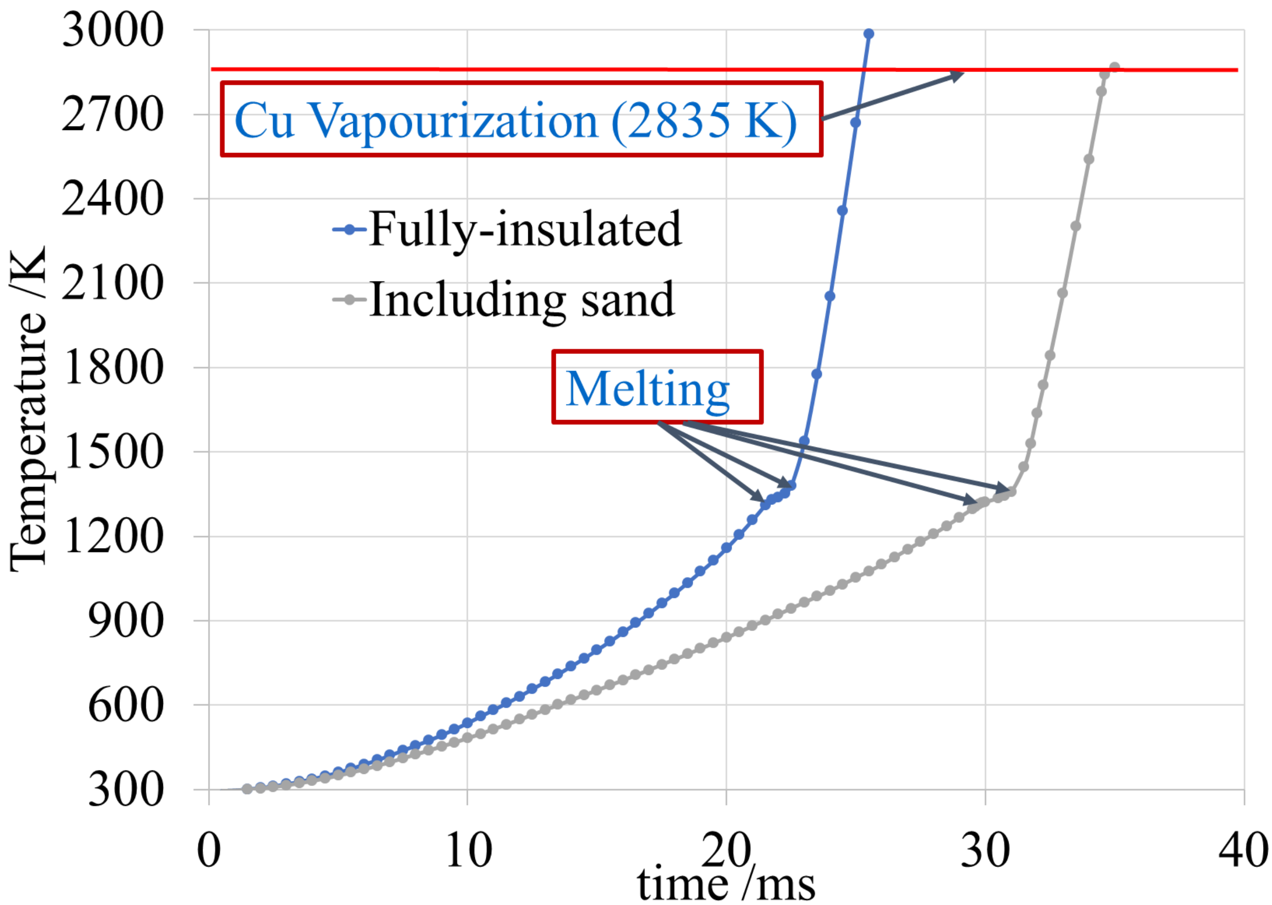

Figure 2. Comparison of numerical results for the temperature variation between fully-insulated vs. sand inclusion cases.

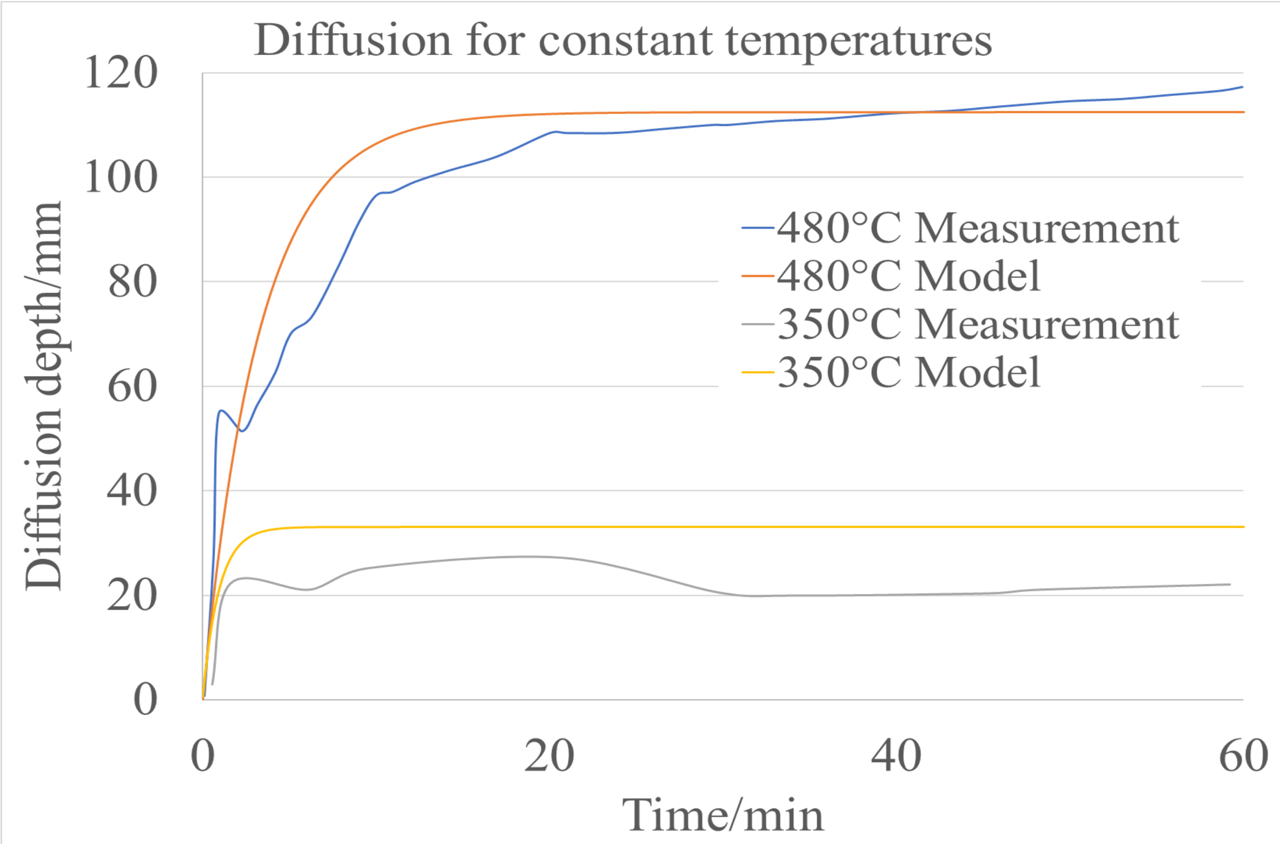

Figure 3. Numerical and experimental results for the diffusion under constant temperature.

In addition to results for the simple element, we also present preliminary results of the diffusion process during M-effect operation. In Fig. 3, we show temporal evolution of diffusion depth for the constant temperatures and the comparison with measurements taken from [6]. It is shown that the diffusion model results are in quite good agreement with the measured data. The diffusion for constant temperature follows exponential function.

IV. Concluding Remarks

Our results show good agreement with the results from experimental tests and with the results of other simulations performed by other groups. This model, when finished, will be used for fuse development in Eaton-Bussmann and it is expected to significantly decrease development time obviating the need for several trial-and-error tests. Nowadays, such simulations can be done on desktop or laptop computers in a reasonable amount of time, thus it is very efficient to utilize numerical modeling in the new product development.

Acknowledgment

The authors gratefully acknowledge the experimental DC pre-arcing time data for both short-circuit and long-overload currents, received from R. Douglass of Eaton-Bussmann, MO, USA.

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