Performance of Cables Subjected to Elevated Temperatures

PETRA ANDERSSON and PATRICK VAN HEES
Fire Technology
SP Swedish National Testing and Research Institute
Box 857
SE-501 15 Borås, Sweden

ABSTRACT

The time to damage, i.e., time to short circuit, and the corresponding temperature within the cable were recorded for two different data cables and one low voltage cable when subjecting the cables to an elevated surrounding temperature. In the experiments it was found that short-circuiting occurred at a certain temperature in the core of the studied cables. The heating of the cables was modeled with the aid of computer programs for thermal analysis and an analytical solution of heat conduction. The experimental results were used to evaluate the different models. Both the analytical solution and the use of the thermal analysis programs turned out to be promising. However, both the analytical solution and the use of computer programs such as TASEF require data of the thermal properties of the cables. This is a complication as such data are not easily accessible. To some extent the thermal properties of the cables could be estimated from the experimental results.

KEYWORDS: cables, functional performance, heat transfer

NOMENCLATURE LISTING

A	Biot number, = hR/k
C_p	specific heat (J/kg/K)
c	rate of temperature rise (°/s)
d	diameter, m
E_{cr}	critical dose (s(kW/m²)^n)
h	effective heat transfer coefficient (W/K/m²)
J_n	n:th Bessel function of first kind
k	thermal conductivity (W/m/K)
m, n	exponents, non dimensional
Nu	nusselt number
$\dot{q}''$	applied thermal radiation (W/m²)
$\dot{q}''_{cr}$	critical thermal radiation level (W/m²)
R	radius of cable (m)
Re	reynolds number
T	temperature (K)
T_{cr}	critical temperature (K or °C)
T_f	equivalent fire temperature (K)
T_s	surface temperature (K)
T_u	surrounding (furnace) temperature (K or °C)
T_0	initial temperature (K or °C)
t_d	time to damage (s)
u	velocity (m/s)

Greek

β_n	n:th root to the equation $\beta J_1(\beta)=AJ_0(\beta)$
ϕ	view factor
κ	thermal diffusivity (m²/s)
ν	kinematic viscosity of air (m²/s)
θ	non dimensional temperature = $(T-T_0)/(T_u-T_0)$
ρ	density (kg/m^3)
τ	non-dimensional time, = $\kappa t/R^2$

INTRODUCTION

Cables are in many cases part of safety systems and hence knowledge of their functional performance is vital. In places where a large amount of cables is located it is essential to know, for example, how many back up systems should be provided and what type of active or passive protection should be used. Examples include nuclear power plants, tunnels, etc.

The functional performance of cables subject to fire is normally tested in two types of tests; small scale or large scale. In large scale tests, such as the tests developed inside CEN TC 127 AH32 in cooperation with CENELEC TC 213, the cable is subjected to fire over a few meters length in a furnace, while in the small scale tests such as the IEC 60331-11 [1] and 12 and EN – 50200 and 50362 the cable is tested over about 1 m length with a flame temperature of 750°C – 880°C depending on method. Some claim that the results from these two test types can not be compared, i.e., that the full scale test is a harder test to pass than the small scale test, a possible explanation for this could be that the heat transfer to the cable is more limited in the small scale test. No independent tests or evidence of this have however been published up to this moment.

The fire load in a real fire can also be very different from the 750°C, ISO 834 curve, etc. used in the tests and therefore it would be useful for consultants etc. to be able to calculate time to short circuit for a cable in any fire when they are conducting risk analyses and constructing new buildings etc. The real temperature can be both much higher (e.g., in tunnels) and lower (e.g., limited fires in large open spaces)

In a previous project [2] the functional performance of cables exposed to thermal radiation was investigated. In that project the results indicated that a certain critical radiation level exists below which no damage will occur for some of the cables tested. For other cables it was not possible to identify such a level. Other investigators [3] have recently found that short circuit seems to occur when the temperature within the cable reach about 200°C.

This paper presents the results from experiments conducted in a tubular furnace on data and low voltage cables where the cables were subject to an elevated temperature. The results are then used to set up a model for calculating time to damage of a cable subject to fire gases. The model proposed is simple in order to meet the demands from a fire safety engineer conducting risk analysis.

EXPERIMENTAL SET-UPS

Experiments were conducted in a tubular furnace. In each test two cables of the same type were used, one live cable with voltage applied to it and one without any voltage but instead a thermocouple was mounted in the core of the cable. The cables used were two data cables and one low voltage cable. The two data cables were a 12 x 2 x 0.5 mm² called F24 and a 8 x 2 x 0.5 mm² called F25 [4]. The low voltage cable was a 5 x 1.5 mm² called Ekk. The Ekk and F25 were F3 classified while the F24 was not. The nominal furnace temperatures ranged from 185 to 300°C. This range was chosen since 200°C is often used as damage criteria when conducting risk analysis. Each of the conductors of the live cable was connected to one of the electrical phases on the switchboard or to the neutral. The AC level for phase 1, 2, and 3 was measured in all experiments.

The live cable (i.e., the cable with voltage applied to it) was mounted on a non-flammable board (type fiber silicate board). The temperature inside the cable was measured in a similar dead cable (i.e., without voltage applied) mounted on the same board. After 2 minutes of pre-measuring time with the voltage connected to the cable, the board was inserted into a pipe shaped electrical furnace in which a constant temperature was maintained.

EXPERIMENTAL RESULTS

The results are presented in Fig. 1 in terms of temperature in furnace vs. time to damage. The temperature measurement in the furnace depends on where the thermocouple was mounted. Figure 2 presents the temperature inside the cable when short circuit occurred.

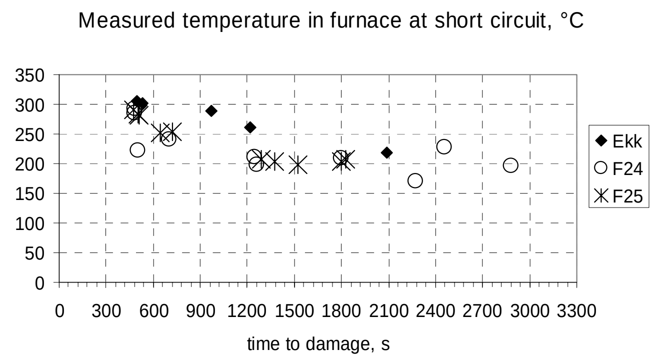

Fig. 1. Measured temperature inside furnace when short circuit occurred as a function of time to damage.

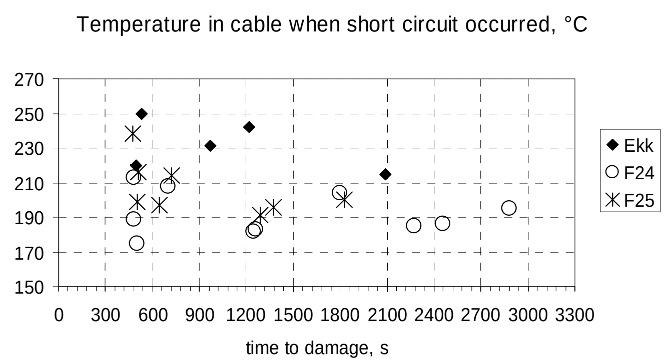

Fig. 2. Temperature inside cable when short circuit occurred as a function of time to damage.

Figure 2 indicates that the critical temperature for the F24 cable is approximately 180°C, for the F25 cable 190°C and for the Ekk 215°C. The varying temperature for short times to damage reflects the fact that when the time to damage is short, the difference between the surrounding temperature and the temperature in the cable is high which creates a large temperature gradient within the cable. This makes it more crucial exactly where the thermocouple for determination of the temperature at failure is located within the cable. The cable temperatures at short circuit are in the same order of magnitude as reported by

Bertrand et. al. [3], i.e., 201°C at a furnace temperature of 250°C, 220°C at 300°C and 223°C at 400°C furnace temperature.

NUMERICAL CALCULATIONS

If the thermal properties are known for the cables then it is possible to calculate the temperature within the cable using computer programs such as HSLAB and TASEF [5]. The results from a few simulations using these programs are presented in Fig. 3 and Fig. 4.

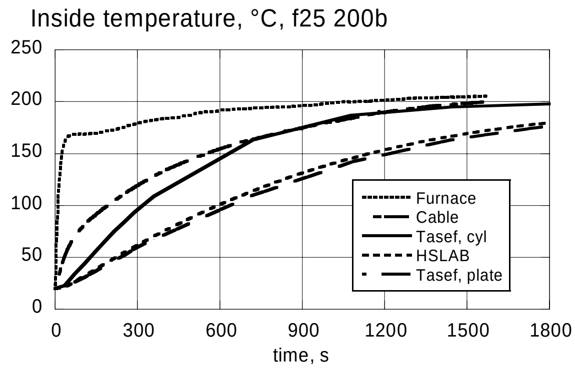

Fig. 3. Measured (F25200b) and calculated inner temperature.

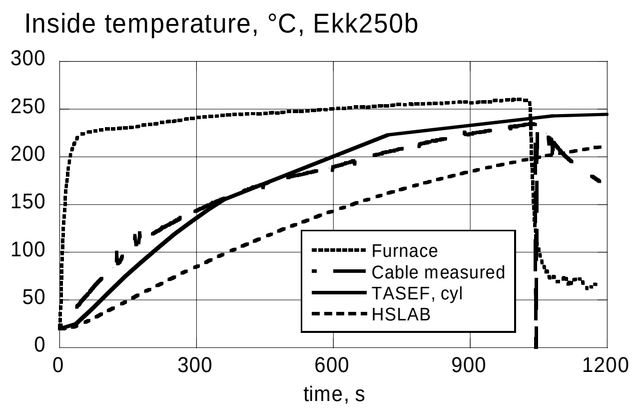

Fig. 4. Simulated and measured inside temperature for the case Ekk250b.

The results are compared to two of the experiments i.e., the F25200b and Ekk250b case [6]. In the simulations the values used for PVC were [7], ρ = 1400 kg/m³, k = 0.16 W/m/K, C_p = 1050 J/kg/K. It was assumed that the cable only consisted of homogenous PVC i.e., the influence of the core wires was neglected. In all calculations the emissivity was set equal to 0.5 while the heat transfer coefficient was set to zero (convection neglected). This is a reasonable assumption for the present test set-up where the exposed cable is completely surrounded by the hot furnace walls and radiation is expected to be the dominating heat transfer mode. HSLAB only simulates plane walls so in that case the cable was approximated with an infinite large plate 1 cm thick but otherwise with the same values of emissivity and the heat transfer coefficient. In addition a TASEF simulation where the cable was approximated as a slab 1 cm thick with the emmisivity 0.5 and convective heat transfer coefficient, $h = 0$ was made as a comparison to the HSLAB simulation. As seen the agreement between these two simulations is good, while they differ significantly from the experimental result as expected. The simulations underestimate the temperature in the beginning but, except the HSLAB/TASEF plate simulations, is more in agreement and even overestimate the temperature later. In particular at temperatures close to the critical inner temperature (i.e., 190°C and 215°C respectively) the temperature is more in agreement and even overestimated for the Ekk case using the cylindrical coordinates in TASEF that results in a conservative time to damage.

It is seen in Fig. 4 that the simulation with HSLAB seriously underestimates the temperature. This is a natural consequence of the fact that HSLAB treats the cable as a slab. The same thing is true for the other high temperature tests (250-300 C). Underestimating the temperature results in an overestimation of time to damage. Therefore it is not acceptable to use HSLAB for the present application with cables.

In one test the surrounding temperature followed a prescribed curve. This was also simulated using TASEF, the result is presented in Fig. 5 with the same values of the emissivity and the heat transfer coefficient i.e., emissivity = 0.5 and $h = 0$.

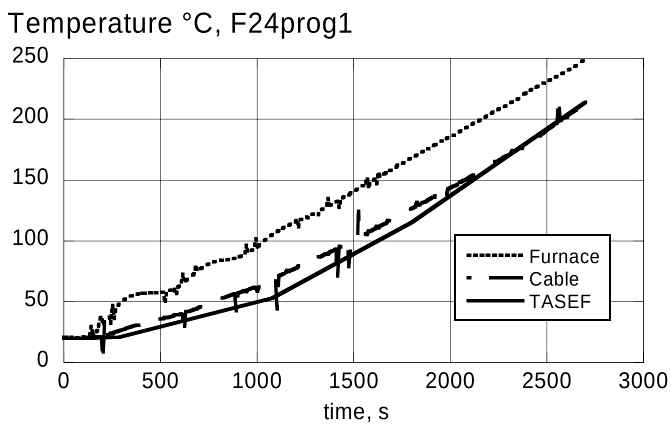

Fig. 5. Measured and simulated inside temperature using TASEF for the case F24prog1.

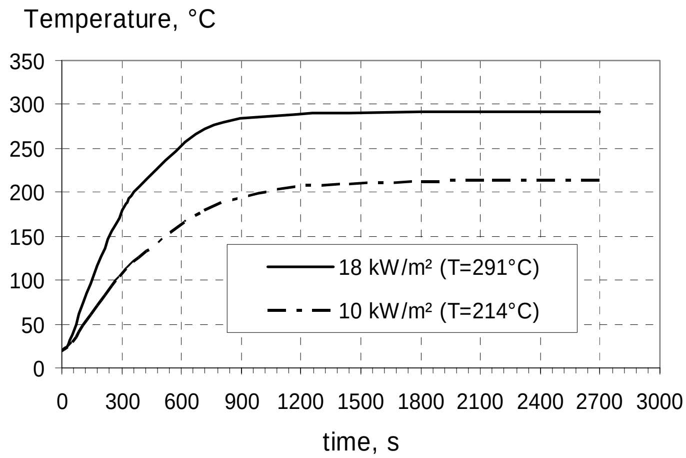

Fig. 6. The calculated temperature inside the cable when it is subject to 10 kW/m² respectively 18 kW/m² thermal radiation using TASEF.

In the work by Andersson and Van Hees [2] the cables were exposed to a prescribed external radiation in the cone calorimeter. The inside temperature was not measured in that case but only time to damage. For the 18 kW/m² case the time to damage was found to be 380-600 s for the F24 cable [2] and 10 kW/m² was found to be close to the critical thermal radiation level below which no damage occurs. The results from simulating the temperature inside the cable when it is subject to external radiation using TASEF are presented in Fig. 6. The radiation is converted to a corresponding fire temperature T_f in these simulations since it was not possible to use TASEF with an applied thermal heat flux and cylindrical coordinates. The corresponding temperature T_f is calculated by

$$T_f = \sqrt[4]{q''/\pi/5.67\cdot 10^{-8}} \quad (1)$$

where $1/\pi$ is the view factor since only one side of the cable is exposed to the radiation.

According to the simulation, the time to damage is about 320 s assuming that the damage temperature is 180°C. This is somewhat faster than the experimental result. In addition the temperature in the simulation levels out at 214°C, which is higher than the critical temperature of 180°C. However, in the simulation the cable is approximated as a solid PVC cable. In reality it contains a copper core that will act as a heat sink. Besides, the thermal radiation is applied over a limited length of the cable, which means that actual longitudinal heat conduction may be important. The effect of this heat sink is estimated by comparing 2D and 3D solutions to the order of 20 - 40°C. If this is subtracted from 214°C we end up close to the critical temperature of 180°C.

ANALYTICAL SOLUTION

Other means to calculate the temperature within the cable is to use an analytical solution for heat conduction in cylindrical geometries [8]. The following dimensionless variables θ, τ and A are introduced:

$$\theta = \frac{T - T_0}{T_u - T_0}; \tau = \frac{\kappa t}{R^2}; A = \frac{hR}{k} \tag{2}$$

where T_u is the surrounding temperature (assumed constant), T is the temperature within the cable, T_0 is the initial temperature of the cable, κ is the thermal diffusivity, R the radius of the cable and k the thermal conductivity of the cable material. The parameter h appearing in the variable A is the effective heat transfer coefficient i.e., it is a coefficient describing the combined heat flux of radiation and convection. The temperature in the cable can then be calculated from

$$\theta = 1 - 2A \sum_{n=1}^{\infty} \frac{J_0(r\beta_n / R)}{(\beta_n^2 + A^2) J_0(\beta_n)} \cdot e^{-\beta_n^2 \cdot \tau} \tag{3}$$

where β_n are the roots to the equation.

$$\beta J_1(\beta) = A J_0(\beta) \tag{4}$$

Here J_n denotes the n:th Bessel function of the first kind. If θ_0 denotes the temperature in the centre of the cable and the series is terminated after the first term one obtains

$$\theta_0 = 1 - \frac{2A \cdot e^{-\beta_1^2 \cdot \tau}}{(\beta_1^2 + A^2) J_0(\beta_1)} \tag{5}$$

Using a heat transfer coefficient (h) of 10 kW/m² gives A = 0.3 and the first root β_1 to Eq. 4 becomes 0.75. This results in $J_0(\beta_1)$ = 0.86. Using these values in Eq. 5 yields

$$\theta_0 = 1 - 1.07 \cdot e^{-0.563 \cdot \tau} \tag{6}$$

In Fig. 7 a comparison is made between the temperature calculated with Eq. 6 and the experimental result.

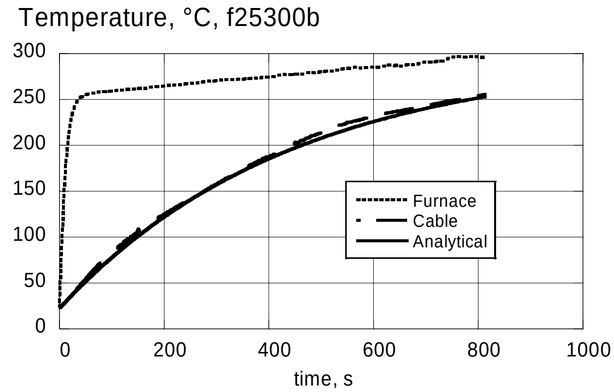

Fig. 7. Comparison between experiment and analytical solution for F25300b.

Time to damage is calculated from Eq. 6 as

$$t_d = \frac{R^2}{\kappa\beta_1^2}\cdot\ln\left[\frac{2A}{(\beta_1^2+A^2)J_0(\beta_1)}\left(1+\frac{T_{cr}-T_0}{T_u-T_{cr}}\right)\right] \tag{7}$$

or

$$t_d = 445\cdot\ln\left[1.01\cdot\left(1+\frac{T_{cr}-T_0}{T_u-T_{cr}}\right)\right] \tag{8}$$

Time to damage was calculated according to Eq. 8 for all the cases except F24prog1, a comparison is presented in Fig. 8. As can be seen the model result in a conservative time to damage except for one of the F24 cases. The time to damage is also very conservative for the F24 case for the lower temperatures. This can be due to that the material data (k, ρ, and C_p) chosen in the calculations are not correct for this cable. Also in the F24 case there were some experiments that gave strange results, this can be due to difficulties in measuring the temperature in this particular cable.

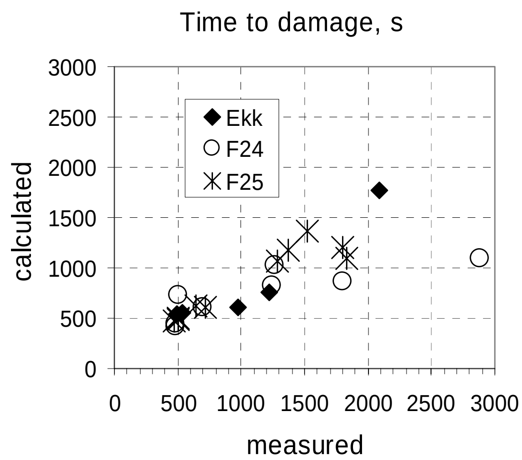

Fig. 8. Comparing calculated time to damage
with experimental values.

In fire situations the temperature around the cable is seldom constant. It is therefore desired that the time to damage can be calculated for any temperature curve. If the temperature follows a curve *F(t)*

$$T_u - T_0 = F(t) \tag{9}$$

and Eq. 2 is rewritten for a step change in T_u-T_0 one obtains

$$\theta = T - T_0 = 1 - 2A\sum_{n=1}^{\infty} \frac{J_0(r\beta_n / R)}{(\beta_n^2 + A^2) J_0(\beta_n)} \cdot e^{-\beta_n^2 \cdot \tau} \tag{10}$$

By the aid of Duhamels theorem this can be transformed into

$$\theta = 2A\sum_{n=1}^{\infty} \frac{\beta_n^2 \cdot J_0(r\beta_n / R)}{(\beta_n^2 + A^2) J_0(\beta_n)} \int_0^{\tau} F(\lambda) \cdot e^{-\beta_n^2 \cdot (\tau - \lambda)} \cdot d\lambda \tag{11}$$

and for the centre of the cable.

$$\theta_0 = 2A\sum_{n=1}^{\infty} \frac{\beta_n^2}{(\beta_n^2 + A^2) J_0(\beta_n)} \int_0^{\tau} F(\lambda) \cdot e^{-\beta_n^2 \cdot (\tau - \lambda)} \cdot d\lambda \tag{12}$$

Especially for the case with a linearly increasing temperature in time, *F(t)=ct*.

$$\theta_0 = \frac{2AcR^2}{\kappa}\sum_{n=1}^{\infty}\frac{\beta_n^2}{(\beta_n^2 + A^2)J_0(\beta_n)}\int_0^{\tau}\lambda \cdot e^{-\beta_n^2\cdot(\tau-\lambda)} \cdot d\lambda \tag{13}$$

or

$$\theta_0 = \frac{2AcR^2}{\kappa}\left(\sum_{n=1}^{\infty}\frac{1}{(\beta_n^2 + A^2)J_0(\beta_n)}\right)\cdot\tau - \frac{2AcR^2}{\kappa}\left(\sum_{n=1}^{\infty}\frac{1}{\beta_n^2(\beta_n^2 + A^2)J_0(\beta_n)}\right) +$$

$$+\frac{2AcR^2}{\kappa}\left(\sum_{n=1}^{\infty}\frac{e^{-\beta_n^2\cdot\tau}}{\beta_n^2(\beta_n^2 + A^2)J_0(\beta_n)}\right) \tag{14}$$

which results in

$$\theta_0 = \frac{cR^2}{\kappa}\cdot\tau - \frac{cR^2}{4\kappa}\left(1+\frac{2}{A}\right) + \frac{2AcR^2}{\kappa}\left(\sum_{n=1}^{\infty}\frac{e^{-\beta_n^2\cdot\tau}}{\beta_n^2(\beta_n^2 + A^2)J_0(\beta_n)}\right) \tag{15}$$

Applying Eq. 14 on the case F24prog1 with c = 230/2700 °/s results in a rather good agreement as presented in Fig. 9.

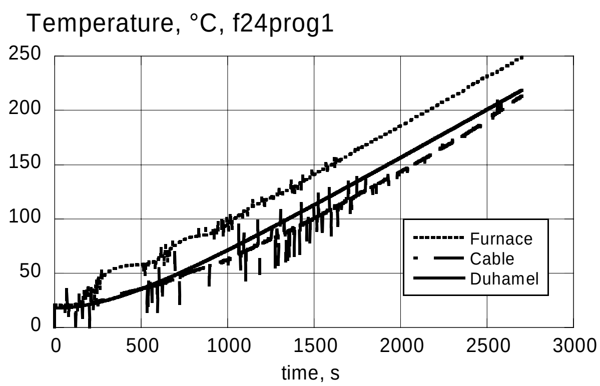

Fig. 9. Comparing the measured and calculated cable temperature in the F24prog1 case.

It would be interesting to test the model in a real fire case and see if the time to damage and temperature within the cable can be can be predicted as good as in the furnace case. In a real fire situation the heat transfer coefficient will be different but, since the model is based on physics, it is likely to work provided that the assumption that the cable short circuit at a certain cable temperature is valid. With Duhamels theorem it is possible to make numerical solutions for any temperature variation in time around the cable.

CONCLUSIONS

It is possible to model the inside temperature with the aid of computer programs such as TASEF and Femlab©. However they require input of the thermal properties of the materials which can be difficult to estimate. It is also possible to calculate the time to damage with the analytical solution, this also requires material data, but these data can to some extent be estimated by trial and error in the analytical solution. It is possible to make a numerical solution for a varying surrounding temperature both by means of the Duhamel theorem and with computer programs. The accuracy in the analytical solutions will not be as good as in numerical solutions because of the necessity of linearising the heat transfer coefficient in the analytical approach (i.e., defining an effective heat transfer coefficient for both radiation and convection). When extrapolating the present results to other scenarios, independent information about the emissivity of the cables, the temperature of the heat source (e.g., gas temperature) and the heat transfer coefficient will be needed.

The model looks promising but there are a few assumptions made that should be checked before one can use the model on a more regular basis.

- The model is only tested on cables with PVC insulation. Cables that have been tested within the project are PVC cables and mainly data cables. It would be interesting to test the model on other cable types as well.
- No temperature measurement within the cable was performed during the experiments with an external thermal radiation applied. One can therefore not be certain that the critical temperature is valid also for the thermal radiation case.
- The model has not been tested in a real fire scenario. The model has only been applied to the experiments in the tubular furnace, there is no guarantee that the critical temperature is true also in a real fire scenario where the heat is applied on a limited area or over the entire cable, the heat transfer coefficient differs from the furnace case, the cable might be subject to mechanical tension etc.
- The model does not include effects of the cable copper core(s). This effect can be substantial if the cable is heated locally and the cable has a large copper core or several copper wires.

In order to base the model on a sound basis one ought to investigate if there is any physical explanation for the critical temperature. If one want to calculate the short circuit time without selecting a fixed temperature it would be necessary to solve the problem by means of a multiphysics problem combining heat transfer with electrical field calculation. This would however imply that one needs to obtain temperature dependent electrical insulation characteristics of the material involved. In this area very little information is available for the applicable temperature ranges.

The model presented in this paper does not take into account effects such as ohmic heating of the cable, different materials in the cable and carbonisation of the polymer. It is easy to add more materials and take ohmic heating into account in the simulations using both of the computer programs while carbonisation requires more work. However the model was developed for a rather quick calculation of whether the cables will survive the fire and does therefore not include all physical effects.

ACKNOWLEDGEMENT

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