

MODELLING THE FIRE BEHAVIOUR OF ELECTRICAL CABLES

Simo Hostikka and Anna Matala

VTT Technical Research Centre of Finland, Espoo, Finland

ABSTRACT

Electrical cables constitute the major part of the fire loads in nuclear power plants and may also serve as ignition sources, contributing significantly to the overall risk. In this paper, the numerical methods for describing the thermal degradation of cable component materials are presented. Analytical techniques based on genetic algorithms for estimating the necessary model parameters from the small and bench scale experimental data have been used and the procedure for parameter estimation is reported. As a special topic, the modelling of the fire retardant cable materials is discussed.

INTRODUCTION

Electrical cables constitute the major part of the fire loads in nuclear power plants and may also serve as ignition sources, contributing significantly to the overall risk. Quite often, the analysis of the fire risks requires numerical fire simulation of cable fires. The single most important challenge of the fire simulation is the description of the fire source in terms of time dependent heat release rate and location. For power plants, this ultimately requires the prediction of fire spread on electrical cables – a topic which does not seem to be of great interest in the other fields of fire safety engineering. The difficulty of cable fire modelling is the fact that the fire heat release rate is specific to the application. It is not possible to use analytical or empirical correlations to prescribe the heat release rate, as it would be for liquid pool fires, for example. Therefore, the fire size must be computed using sufficiently detailed numerical models for both the cable behaviour and the thermal feedback from the gas phase flames.

In the context of fire CFD, the solid phase thermal behaviour is usually solved simultaneously with the gas phase mass and heat transfer. To simulate the solid phase thermal response, one needs to approximate the physical geometry with something being solvable by the available heat conduction solver, usually a one-dimensional solver, and to prescribe the model parameters. These parameters include the structural, thermal and reaction-related properties for the materials. The pyrolysis reaction paths and the associated kinetic coefficients must be specified. The determination of material model parameters is a crucial and challenging phase of the simulation procedure, because the fire development strongly depends on many of the parameters, and because the well-established methods for finding these parameters are not yet available. Indeed, there are plenty of experimental techniques to study the thermal behaviour of a material, but the techniques to exploit these tests and to estimate the material parameters using the test results are just evolving.

In this work, the numerical methods for describing the thermal degradation of cable component materials are presented and implemented as part of the Fire Dynamics Simulator (FDS) software [1]. Analytical techniques based on genetic algorithms [2] for estimating the necessary model parameters from the small and bench scale experiments are used. As a special topic, the modelling of the fire retardant cable materials is discussed.

THERMAL DEGRADATION MODEL OF ELECTRICAL CABLES

Mathematical Model of Thermal Degradation

The thermal degradation process of cables is modelled using the general pyrolysis model of FDS [1]. Each solid phase wall cell or sub-grid scale element can be associated

with a one-dimensional multi-layered, multi-component structure where each material may undergo a number of reactions producing other solids and gases. In this model, a one-dimensional heat conduction equation for the solid phase temperature $T_s(x,t)$ is applied in the direction x pointing into the solid (the point $x = 0$ represents the surface). For cylindrical object, the co-ordinate direction is opposite (the surface is located at $r = R$).

$$\text{Cartesian: } \rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} k_s \frac{\partial T_s}{\partial x} + \dot{q}_s''' \quad (1)$$

$$\text{Cylindrical: } \rho_s c_s \frac{\partial T_s}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} r k_s \frac{\partial T_s}{\partial r} + \dot{q}_s''' \quad (2)$$

The boundary condition at the sample surface is:

$$\text{Cartesian: } -k_s \frac{\partial T_s}{\partial x}(0,t) = \dot{q}_c'' + \dot{q}_r'' \quad (3)$$

$$\text{Cylindrical. } k_s \frac{\partial T_s}{\partial r}(R,t) = \dot{q}_c'' + \dot{q}_r'' \quad (4)$$

The source term \dot{q}_s''' consists of chemical reactions and radiative absorption. The conductivity and volumetric heat capacity of the solid are defined:

$$k_s = \sum_{\alpha=1}^{N_m} X_{s,\alpha} k_{s,\alpha}; \quad \rho_s c_s = \sum_{\alpha=1}^{N_m} \rho_{s,\alpha} c_{s,\alpha} \quad (5)$$

Here, N_m is the number of material components forming the solid. $\rho_{s,\alpha}$ is the component density:

$$\rho_{s,\alpha} = \rho_s Y_{s,\alpha} \quad (6)$$

where ρ_s is the density of the multi-component material, computed as a sum of components, and Y_{α} is the mass fraction of the material component α . $X_{s,\alpha}$ is the volume fraction of the component α ,

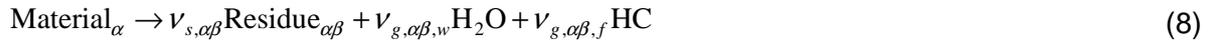
$$X_{s,\alpha} = \frac{\rho_{s,\alpha}}{\rho_{\alpha}} \left/ \sum_{\beta} \frac{\rho_{s,\beta}}{\rho_{\beta}} \right. \quad (7)$$

where ρ_{α} is the density of material α in its pure form. Multi-component solids are defined by specifying the mass fractions Y_{α} , and densities ρ_{α} , of the individual components. The main assumptions of the pyrolysis model are

- instantaneous release of volatiles from solid to the gas phase,
- local thermal equilibrium between the solid and the volatiles,
- no condensation of gaseous products, and
- no porosity effects.

Each material component may undergo several competing reactions, and each of these reactions may produce some other solid component (residue) and gaseous volatiles according to the yield coefficients ν_s and $\nu_{g,\gamma}$, respectively. These coefficients should usually sum up to one but smaller yields may also be used to take into account the gaseous products that are not explicitly included in the simulation.

Consider the material component α that undergoes $N_{r,\alpha}$ separate reactions. We will use the index β to represent one of these reactions:



In this particular reaction, condensed phase residue, water vapour and hydrocarbon fuel are produced.

The local density of material component α evolves in time according to the condensed phase species conservation equation:

$$\frac{\partial}{\partial t} \left(\frac{\rho_{s,\alpha}}{\rho_{s0}} \right) = - \sum_{\beta=1}^{N_{r,\alpha}} r_{\alpha\beta} + S_{\alpha} \quad (9)$$

explaining that the mass of component α is consumed by the solid phase reactions $r_{\alpha\beta}$ and produced by other reactions. $r_{\alpha\beta}$ is the rate of reaction β in units [1/s] and ρ_{s0} is the initial density of the material layer. S_{α} is the production rate of material component α as a result of the reactions of the other components. The reaction rates are functions of local mass concentration and temperature, and calculated as Arrhenius functions:

$$r_{\alpha\beta} = \left(\frac{\rho_{s,\alpha}}{\rho_{s0}} \right)^{n_{s,\alpha\beta}} A_{s,\alpha\beta} \exp\left(-\frac{E_{s,\alpha\beta}}{RT_s}\right) \quad (10)$$

S_{α} is the sum over all the reactions, where the solid residue is the material α :

$$S_{\alpha} = \sum_{\alpha'=1}^{N_m} \sum_{\beta=1}^{N_{r,\alpha'}} \nu_{s,\alpha'\beta} r_{\alpha'\beta} \quad (\text{where residue}_{\alpha'\beta} = \text{material}_{\alpha'}) \quad (11)$$

The volumetric production rate of each gaseous volatile is:

$$\dot{m}_{\gamma}''' = \rho_{s0} \sum_{\alpha=1}^{N_m} \sum_{\beta=1}^{N_{r,\alpha}} \nu_{g,\alpha\beta,\gamma} r_{\alpha\beta} \quad (12)$$

It is assumed that the gases are transported instantaneously to the surface, where the mass fluxes are given by:

$$\text{Cartesian:} \quad \dot{m}_{\gamma}'' = \int_0^L \dot{m}_{\gamma}''' dx \quad (13)$$

$$\text{Cylindrical:} \quad \dot{m}_{\gamma}'' = \frac{1}{R} \int_0^R \dot{m}_{\gamma}''' r dr \quad (14)$$

The chemical source term of the heat conduction equation consists of the heats of reaction:

$$\dot{q}_{s,c}''' = -\rho_{s0} \sum_{\alpha=1}^{N_m} \sum_{\beta=1}^{N_{r,\alpha}} r_{\alpha\beta} H_{r,\alpha\beta} \quad (15)$$

Equations (1) and (2) are discretised using the method of finite differences and integrated in time using the implicit Crank-Nicholson scheme (see FDS documentation [1] for more details).

Estimation of Model Parameters

An important step of cable modelling is the specification of reaction schemes and estimation of the corresponding model parameters. This step is as important as the actual model formulation. Based on their role in the computational model, the model parameters can be classified as ‘structural’, ‘thermal’ or ‘reaction’ parameters.

Structural parameters are the number of layers, layer thicknesses, material mass fractions $Y_{s,\alpha}$ inside each layer, geometry (Cartesian or cylindrical) and the type of the background boundary condition. Although some of these may seem to be straight forward to determine, the actual specification is usually a modelling decision.

Reaction parameters consist of kinetic parameters (the pre-exponential factors $A_{s,\alpha\beta}$, activation energies $E_{s,\alpha\beta}$ and reaction orders $n_{s,\alpha\beta}$), yield coefficients ($v_{s,\alpha\beta}$ and $v_{g,\alpha\beta,\gamma}$), the heats of reaction $H_{r,\alpha\beta}$ and the net heat of combustion of the resulting gaseous volatiles $H_{c,\alpha,\gamma}$ for the enthalpy computations.

Thermal parameters naturally include the densities, conductivities, specific heats and surface emissivity. If the internal thermal radiation plays a role, the (gray) absorption coefficient κ_α must be specified for each material. The conductivities and specific heat values often depend on temperature.

Table 1 lists these parameters for the exemplary cable. In addition, various parameters are available to fine-tune the numerical behaviour of the model, see FDS documentation [1] for more information. Furthermore, more simple methods for modelling the material behaviour are available, if necessary.

The current understanding is that the reaction parameters should be determined from very small-scale experiments using the thermogravimetry, and the thermal and structural parameters either from direct measurements or from bench-scale experiments, such as the cone calorimeter. However, some authors have also determined all the parameters, both thermal and kinetic, using just cone calorimeter data [3]. The actual methods for the parameter estimation may range from simple rules of thumb to numerical optimization techniques. Recently, the genetic algorithms have been used to determine the kinetic parameters for polyurethane foam [4], natural (cellulosic) materials [2], [6], polymers [2], [5], and intumescent coatings [6].

Our procedure for parameter estimation is outlined in Figure 1. First, the cable sample is broken into layers or components of material mixtures, and the densities of layers are measured.

In the second phase, thermogravimetric analysis (TGA) is used to determine the (effective) material mass fractions, their reactions and reaction products. The kinetic parameters are estimated, using e.g. GA, and the reaction paths are updated if satisfying results are not obtained. If the reaction enthalpies are measured at the same time with the TGA tests using either Differential Thermal Analysis (DTA) or Differential Scanning Calorimetry (DSC), the test is called Simultaneous Thermal Analysis (STA). STA experiments are rarely accurate enough for quantification of the heats of reaction, but sufficiently accurate for qualitative specification if the reactions are endothermic or exothermic. For this reason, the tests should be performed both in air and inert (N_2) atmospheres. The obtained information can be used to conclude the roles of different material components in the degradation process, helping in the specification of mass fractions and reaction paths. The decisions concerning the reaction paths are extremely important because many of the parameters depend on them. Quite often, the best results are not obtained by the most complicated model. Instead, one should try to find the simplest

possible definition of material components and reactions being able to reproduce the major dynamics.

Table 1 Material parameters for the FRNC cable

Quantity	Unit	Sheath_V	Sheath_S	Filler 1	Filler 2	Insulation	Char_S	Char_F
Material mass fractions								
Layer 1		0.14	0.86	0	0	0	0	0
Layer 2		0.07	0.02	0.71	0	0.2	0	0
Thermal								
ρ_α	kg/m ³	1373	1373	1745	1361	840	649	15.0
$c_{s,\alpha}$	kJ/(kg·K)	1.5...2.3 ¹	1.5...2.3 ¹	2.5	2.43	3.46	2.0	1.50
$k_{s,\alpha}$	W/(m·K)	0.01	0.08	0.6	0.6	0.8	0.5	0.1
ε_α	-	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$H_{c,\alpha,\gamma}$	kJ/kg	0	5.5 E+04	4.0 E+04	3.0 E+04	4.0 E+04		
$H_{r,\alpha\beta}$	kJ/kg	4.0 4E+03	2.35 E+02	2.10 E+03	1.00 E+02	4.00 E+03		
κ_α	1/m	∞	∞	∞	∞	∞	∞	∞
Kinetic								
$N_{r,\alpha}$	-	1	1	1	1	1	0	0
$n_{s,\alpha\beta}$	-	1.0	1.0	1.87	1.76	0.80		
$A_{s,\alpha\beta}$	1/s	5.43 E+11	6.01 E+18	5.93 E+08	1.30 E+08	1.96 E+17		
$E_{s,\alpha\beta}$	kJ/kmol	1.80 E+05	3.00 E+05	1.39 E+05	2.08 E+05	2.78E+05		
Residue		-	CHAR_S	FILLER_2	CHAR_F	-		
$v_{g,\alpha\beta,water}$	kg/kg	1	0	0	0	0		
$v_{g,\alpha\beta,fuel}$	kg/kg	0	0.45	0.25	0.54	1		
$v_{s,\alpha\beta}$	kg/kg	0	0.55	0.75	0.46	0		

¹⁾ Temperature dependant $c_{s,\alpha}$ from DSC experiment; temperature range 20 ... 360 °C

In the third phase, direct measurements of thermal properties and reaction enthalpies can be utilized. DSC tests, for instance, can be used to determine both the specific heats and reaction enthalpies. However, their results must be interpreted with the specified reactions paths in mind.

Finally, in the fourth phase, the bench-scale experiments, such as cone calorimeter tests are used to estimate the details of the approximated structure and unknown thermal parameters. If the results of a multi-component and multi-layer product are not satisfactory, the structure approximation should be revised. It may also be necessary to go back to the second phase, and try a different reaction path. To reduce the uncertainty of flame heat flux modelling, the cone calorimeter tests should be performed both in air and inert atmospheres.

As there are no direct measurements of all the thermal properties, many of them have been estimated. It is therefore possible, and even likely that the model's incapability to capture some physical processes is compensated within the structural and thermal parameters. Therefore, it is important to understand that the estimated parameters should not be treated as fundamental material properties, but rather as model parameters.

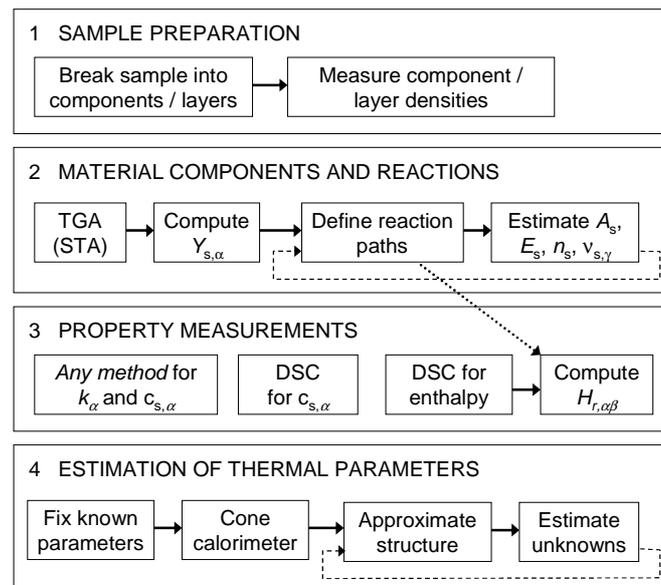


Figure 1 Parameter estimation procedure

Modelling Mineral Filler Based Flame Retardants

Mineral fillers form an important class of flame retardants of polymer materials. Two common filler materials are Aluminium (tri) hydrate $\text{Al}(\text{OH})_3$ (ATH) and Magnesium (di) hydrate $\text{Mg}(\text{OH})_2$ (MDH). These materials are added to the polymer during the processing phase. When the material is heated, they decompose yielding water vapour and metal oxide. They have three primary mechanisms of flame retardancy:

1. The decomposition of the molecule is strongly endothermic, and takes energy that would otherwise heat up and decompose the actual polymer.
2. Increased formation of char, which acts as a protecting layer.
3. Dilution of combustible gases by water vapour.

The relative importance of the above mechanisms depends on the fire scenario. In cone calorimeter, the first two are probably more important than the third one. The practical experiences have shown that the structural issues, such as the use of additional layers with mechanical and electrical purposes may have a strong effect on the cone calorimeter results.

All three mechanisms can be taken into account in the simulations. The first one can be implemented by specifying the material layer as a mixture of non-combustible, degrading material and combustible polymer. The second one is a direct consequence of the TGA findings, and implemented via the yield coefficients. The third mechanism can be achieved by taking into account the additional water vapour. However, its importance has not been shown so far. An example of simulated flame retardancy will be presented in the results.

RESULTS OF FLAME RETARDANT CABLE PYROLYSIS

A pyrolysis model was created for a Prysmian FRNC 0.6/1 kV power cable of type N2XCH 3x2.5. The outer diameter of the cable is 13 mm. The experimental data included.

- STA = TGA + DSC, air and N_2 (Netzsch STA 449C), heating rates 2, 5, 10 and 20 K/min
- DSC in N_2 at 10 K/min heating rate (Mettler Toledo Differential Scanning Calorimeter model DSC820 system STARe SW 8.10)
- Standard cone calorimeter in air, 50 kW/m^2 heat flux level

Based on the small-scale experimental data, the reaction schemes were prescribed. They are summarized in the left part of Figure 2. Two different mechanisms were considered for the flame retardancy of the sheath:

Sheath 1 (Dummy): The reaction path makes no assumption about the actual material used for flame retardancy, and is based solely on the experimental findings. According to the TGA and DSC tests, 14 % of the initial mass evaporates as non-combusting volatiles and the rest undergoes reaction producing combustible volatiles and char.

Sheath 2 (MDH): The flame retardant is assumed to be magnesium (di) hydroxide (MDH). The flame retardancy of this material is based on the degradation of MDH into magnesium oxide and water vapour at > 300 °C temperature. Based on the literature [7], the energy requirement for this reaction is 1250 ... 1370 J/g MDH. Calculating from the molar masses involved in the above reaction, 30.9 % of the mass of the flame retardant evaporates as water leaving a residue yield of 69.1 %. As the total observed evaporating mass is 14 %, the mass-fraction of the flame retardant must be 45 % of the mass of the sheath. The rest of the sheath is degrading to char and fuel gas.

The kinetic parameters of the three cable components were estimated from TGA data using genetic algorithms. The results are shown in Figure 2 (right) and Figure 3. Both reaction paths of the sheath accurately reproduced the experimental TGA graphs.

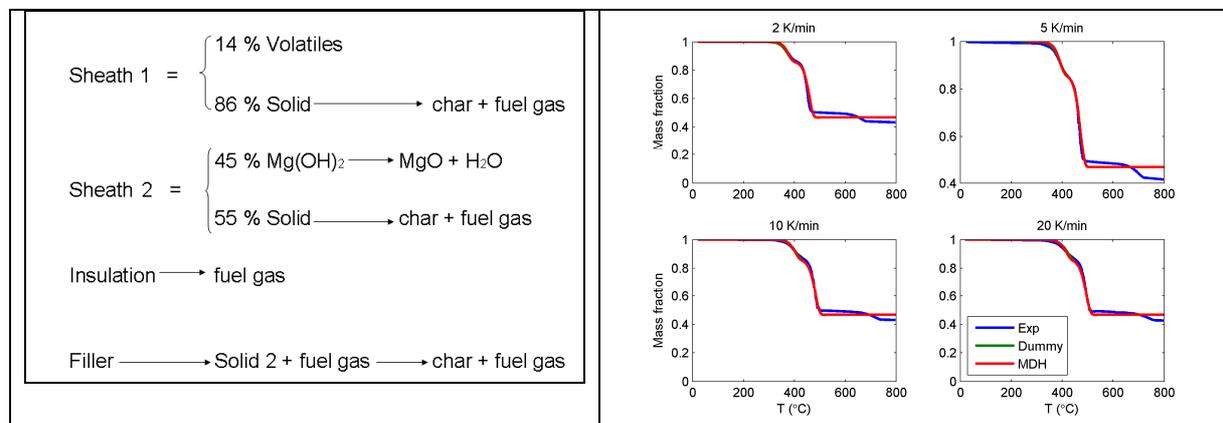


Figure 2 Reaction schemes of the cable components (left) and the experimental and simulated TGA of FRNC cable sheath (right)

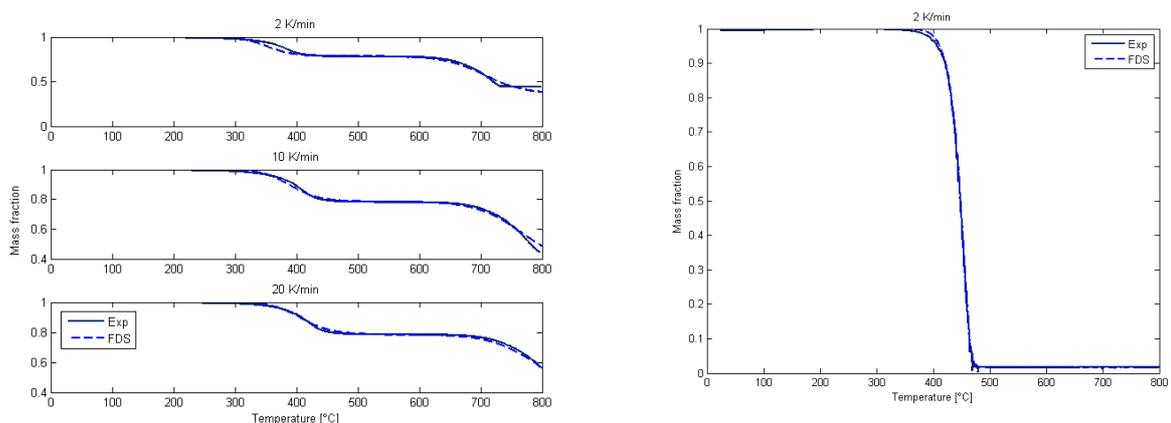


Figure 3 TGA of FRNC cable filler (left) and insulation (right), experimental and simulated

Next, the temperature dependent specific heat and reaction enthalpies of the sheath material were measured using DSC. Finally, the thermal and structural parameters were estimated from standard cone calorimeter experiment, first using GA and making manual

adjustments in the end. It was found, that for such complicated samples, GA may not find the best possible sets of parameters.

The complex cable structure was approximated as two layers: The first 1.2 mm thick layer was pure sheath material, and the second, 9.0 mm thick layer was a mixture of sheath, filler and insulation materials. Additional third layer was added for the substrate material. Sheath 1 (dummy) scheme was used for the cable sheath. The experimental and model surface densities in units [kg/m²] (mass per unit area) of the three components (sheath, filler, insulation) were 6.4/5.3/1.1 and 2.8/9.0/2.5, respectively. The differences are probably due to the uncertainty of effective burning area in the experiment, and the layer-like approximation of cylindrical cables. The results are shown in Figure 4 for heat release rate, mass loss rate and effective heat of combustion. It is important to monitor all three variables to ensure realistic behaviour in both mass and energy flows. When doing the comparison, one must make sure that the numerical and experimental results are computed in the same way. The resulting parameters are listed in Table 1. The total number of model parameters is around 120.

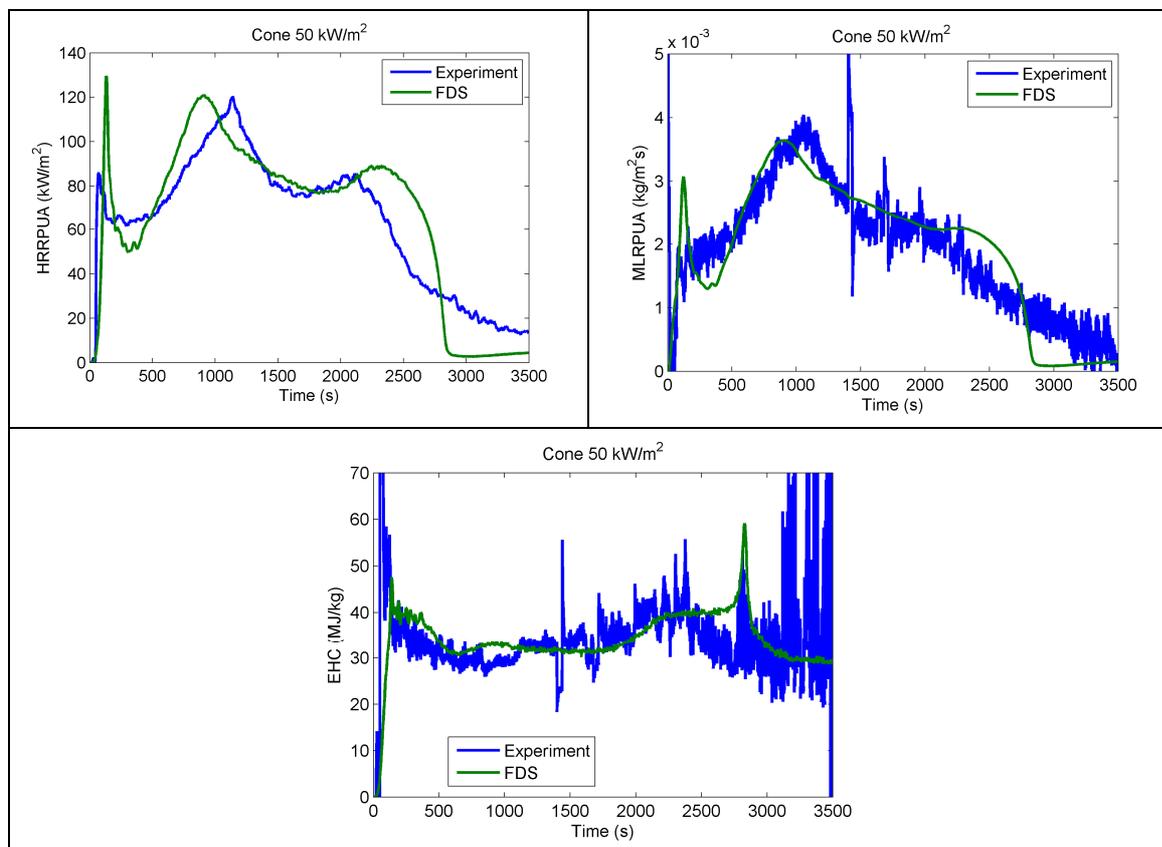


Figure 4 Experimental and simulated cone calorimeter results: heat release rate (top left), mass loss rate (top right) and effective heat of combustion (bottom)

CONCLUDING REMARKS

Numerical simulation model for the thermal degradation of electrical cables is presented and implemented as part of the FDS. Due to the complexity of the multi-layered multi-component material model with multiple reactions, the number of model parameters becomes high. The efficiency and reliability of parameter estimation procedures is therefore essential for the applicability in real problems. The application on flame retardant cable showed that the current methods using genetic algorithms can serve as the first phase of estimation, but adjustments are often needed.

The current model was used to model the flame retardant effects by mineral fillers. The thermal effects are reproduced well enough for practical purposes, but the model's capability to take into account the physical complexity of the cables, such as metal foils and electrical shields, is still unknown. However, the model in its current form has already found applications in real nuclear power plant safety analysis.

Next step from the solid phase modelling is the coupling to the large-scale fire model, and the validation of the complete approach. Much research is needed to overcome these challenges and to proceed towards good engineering practices because neither the experimental methods nor the analytical techniques for determining all the necessary parameters are well established.

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