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External heating of electrical cables and auto-ignition investigation

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HIGHLIGHTS

- Electrical cables pyrolysis and flammability have been studied.
- Two different experimental setups were used to study cables mass loss and flammability.
- A 1-D thermal model for cables mass loss and temperature is proposed.
- Spontaneous and piloted ignitions have been investigated.

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ABSTRACT

Electric cables are now extensively used for both residential and industrial applications. During more than twenty years, multi-scale approaches have been developed to study fire behavior of such cables that represents a serious challenge.

Cables are rather complicated materials because they consist of an insulated part and jacket of polymeric materials. These polymeric materials can have various chemical structures, thicknesses and additives and generally have a char-forming tendency when exposed to heat source.

In this work, two test methods are used for the characterization of cable pyrolysis and flammability. The first one permits the investigation of cable pyrolysis. A description of the cable mass loss is obtained, coupling an Arrhenius expression with a 1D thermal model of cables heating. Numerical results are successfully compared with experimental data obtained for two types of cable commonly used in French nuclear power plants. The second one is devoted to ignition investigations (spontaneous or piloted) of these cables.

All these basic observations, measurements and modelling efforts are of major interest for a more comprehensive fire resistance evaluation of electric cables.

1. Introduction

Ignition and burning of electrical cables are possible causes of fires in residential or industrial buildings. Moreover, cables may also lose their functions or be less efficient when exposed to heat sources (progressive change in resistance, deterioration of the signal quality, short-cut). Electrical cables have an insulation layer which is flammable and may be decomposed at high temperatures to produce combustible gases.

This problem is of major interest because of the increasing use of power and communication cables in our surroundings. Several works have been published in the last 5 years about electrical cable fires. Most of them are experimentally dealing with pyrolysis and thermal degradation of cables (Passalacqua et al., 2013 [1], Mo et al., 2013 [2], Fisher et al., 2015 [3]). Passalacqua et al. [1] characterized experimentally the ignition of ITER electric cables, both at smale and large scales. They found the critical radiative heat flux leading to pyrolysis and ignition and studied the flame propagation speed. They also investigated the influence of cable trays geometry. Mo et al. [2] studied the thermal degradation behavior of cross-linked polyethylene cables using thermogravimetric and differential scanning calorimetry techniques. More recently, Fisher et al. [3] studied the failure of electrical cables widely used in residential electric circuits in the United States. They studied the time to cable failure and found that it was highly dependent on the cable temperature. Shea 2011 [4] made several experiments to study the possible conditions leading to hazards in residential circuits. They studied current arc energies and compared them to the ignition caused by volatile gases produced by pyrolysis or degradation of wires insulation. First

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Nomenclature

c_p	Specific heat ($J\,kg^{-1}\,K^{-1}$)
E	Activation energy
g	Acceleration of gravity ($m\,s^{-2}$)
h	Heat transfer coefficient ($J\,m^{-2}\,K^{-1}\,s^{-1}$)
k	Pre-exponential factor
L	Characteristic length (m)
$\dot{m}''$	Burning rate per unit area ($kg\,m^{-2}\,s^{-1}$)
$\dot{q}$	Heat flux ($J\,s^{-1}$)
Q	Energy *(kJ)*
r	External radius of elementary disk (m)
R	Ideal gas constant
t	Time (s)
T	Temperature (K)

Greek symbols

λ	Thermal conductivity ($J\,m^{-1}\,K^{-1}\,s^{-1}$)
ε	Emissivity
ρ	Gas density ($kg\,m^{-3}$)
σ	Stefan-Boltzmann constant ($J\,m^{-2}\,K^{-4}\,s^{-1}$)
μ	Dynamic viscosity ($N\,s\,m^{-2}$)

Subscripts:

a	Air
e	External
0	Initial
f	Final
j,c	Carbonaceous residue
j,g	Pyrolysis gases
r	Reference
rad	Radiative

experimental results on thermal degradation of PVC cable were given in Benes et al., 2004 [5]. They used thermogravimetry coupled to mass spectrometry and Fourier transform infrared spectroscopy to study PVC cable degradation under different atmospheres. We can also note the numerical contribution of Ferng and Liu 2011 [6]. They used the CFD code Fire Dynamic Simulator to investigate the burning characteristics of electric cables used in nuclear power plant.

Various standards and tests have been developed to investigate the flammability properties of electrical cables. Some tests related to external or internal heating rates have been reported in [7–9] and Hirschler [10] has given a detailed review on the current fire and flammability test methods on electrical cables. He has also reported a number of different test methods [11–13].

Even if non-combustible cables represent the most valuable solution to reduce fire risk, they are too expensive to be commonly used. Thus, only some chemical species such as halogen or magnesium hydroxide are generally added to sheaths to improve their fire resistance. Nevertheless, although the thermo-physical processes taking place in the combustion of cables are similar to those taking place during combustion of constitutive solid polymer fuels, they are more complex due to the different types of material layered in the jacket. Other parameters can play a role in the flammability of cables, such as the interactions between the jacket and the conductor, but also to the configuration of the cables in trays.

Despite the importance of the problem, fundamental information is still lacking and a lot of research efforts have to be done in this field.

In this context, the present work focuses on the burning characteristics of electrical cables, namely the external heating and the flammability of cables exposed to external heating. The cables tested are cables commonly used in French nuclear power plants.

Two types of experiments are carried out. The first type by using the "PITCAIRN" furnace, devoted to heating and degradation studies of cable samples. The second type by using the "Electric Cable Ignition Test Bench" developed by the PPRIME Institute in Poitiers (France), devoted to the determination of spontaneous and piloted ignition temperature limits and delays.

Heating and thermal degradation data are compared with the results of a numerical model. The agreement between experiments and simulations is satisfying and the analysis provides insight about potential approaches for more precise descriptions of combustion of electrical cables.

2. Experiments

2.1. Apparatus

The PITCAIRN furnace is composed of a stainless steel cylinder, 130 cm high and 21.35 cm in inner diameter, surrounded by an isolating jacket. This cylinder is heated with electric coils permitting to reach a maximum temperature of 560 °C on its surface. It can be swept by air or neutral gas. The cable samples (25 cm long) are axially suspended from a METLER load cell which is able to measure fuel consumption as a function of time during a test. The fuel mass loss rate was determined by the rate of pyrolyzed gas leaving the cable. The load cell has a response time of 60 ms, and the uncertainty of measurements is within 5%. Cable surface and central temperatures were measured with chromel-alumel thermocouples (type K) of a 0.5 mm wire. As stated in the standard NF EN 60–584, the uncertainty of type K thermocouples is 1.5 °C between −40 °C and +375 °C. These thermocouples are inserted along a diameter of the cable, showing on the surface.

Different constant heating rates (ranging between 10 and 100 °C/min) can be used to reach 560 °C, which is the regulation temperature of the furnace. Heat flux measurements on the inner wall, using radiometers, have shown that radiative flux is nearly uniform in the central zone of the furnace (35–90 cm). Radiant heat flux was measured by means of a water-cooled Gardon-gauge-type radiometer (MEDTHERM: a cylinder stainless steel pan, 1 inch deep, with a diameter of 1 inch) working in the range 0–2 $W\,cm^{-2}$ and equipped with a window (with a diameter of 6 mm). The radiometer was water cooled and was purged. The water cooling tubes are 1/8 inch diameter stainless steel. The addition of a window eliminates the convective heat flux from the sensor but restricts the spectral content of the radiation to the one of its spectral transmittance. The window used was in calcium fluoride that offers a useful range of spectral transmittance between 0.3 and 11.5 μm. The radiation form factor is then slightly reduced but the calibration takes this reduction into consideration. The uncertainty in flux measurements was on the order of 3 %.

Cable samples are positioned in this zone and are therefore receiving a nearly uniform irradiation. Its value is evaluated from the inner wall temperature measurements and a calculation of view factors between two coaxial cylinders (furnace and sample). It is noteworthy that convective heat transfer is low compared to radiation heat transfer. Fig. 1 shows a scheme of the "PITCAIRN" apparatus.

The "Electric Cable Ignition Test Bench" is used for studying spontaneous and piloted ignition of cable samples (delays and limits). The process can be defined as the occurrence of flaming ignition after the sample has been quickly put into hot air. The apparatus is made of a cylindrical furnace (ceramic tube, 45 cm high and 7.2 cm in inner diameter, heated by coils imbedded in a refractory cement)