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CFD SIMULATION OF CABLE TRAY FIRES

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SUMMARY

The classification of the fire hazard associated with flame spread along runs of cables poses a challenging problem for building services installation and design. Detail of the particular installation – the configuration of cables, whether in bundles or planar webs, the design of the supporting structure and the ventilation conditions – may play a significant role in the response to fire as the physical and chemical properties of the cable materials themselves. A CFD-based methodology has been developed for the simulation of such flame spread in which the localised burning of the cable has been simplified in such a way that the key features of time-to-ignition and heat release (or, more specifically, mass loss rate) are taken from measurements of these properties in a cone calorimeter. This model has been incorporated in the field modelling code SOFIE and coupled with existing sub-models describing buoyant turbulent flow, combustion and heat transfer. The approach is demonstrated in applications to cable tray configurations that have been examined experimentally.

INTRODUCTION

Extended cable runs, for both electrical transmission and, of increasing importance, data links and communications, are important installation features in power plants, vehicles, transportation tunnels and buildings. They link zones that might otherwise be quite separate and are often hidden in voids and shafts that restrict opportunities for inspection. Their flammability and potential for toxic smoke release requires that an assessment be made of the fire hazard that they might represent. This task is made complicated at two levels: firstly, by our incomplete understanding of the underlying physical and chemical processes occurring in and around the cable in the event of fire and secondly the dependence, in any particular scenario, on the detail of the installation.

The incorporation of detailed representations of the burning of complex items into the broader context of fire scenarios is an uncertain process, whether the starting point for the approach is a mathematical model or a well-defined test method. The extent to which such a sub-model can or should reflect the local conditions in the larger scenario – through spatially and temporally-varying rates of radiation heat transfer or ventilation conditions, for example – cannot be confidently prescribed *a priori*. In principle, numerical simulation of the complete scenario, embracing a comprehensive range of physical scales, resolves this difficulty in a fundamental manner. In practice, it too is constrained at the sub-model level of description. The present paper explores the

potential of CFD (field modelling) in the analysis of flame propagation along a web of cables installed in a vertically mounted tray.

The numerical simulations are undertaken within the framework of the CFD code SOFIE, developed at Cranfield specifically for fire applications but which has been made quite widely available within the international fire research community.

MODEL BACKGROUND

The basic features of SOFIE have been reported in the literature [1,2,3], including both the treatment of combustion chemistry and of radiative exchange, incorporating soot. The description here is therefore restricted to those elements specific to the cable tray fire application.

In earlier studies of flame spread over solid materials [3,4], charring and non-charring, we have investigated alternative approaches to the description of solid pyrolysis, ranging from detailed finite-difference analysis of heat and mass transfer within the solid to semi-empirical treatments based on an overall heat of gasification. The multi-element character of cables, which introduces a variety of differing physical and chemical properties on very small scales, makes their detailed modelling computationally unattractive within the wider framework of fire simulation. The localised burning of the cable has therefore been simplified to the extent that the key characteristics of time to ignition and subsequent rate of heat release (or, more specifically, mass loss rate) are taken directly from measurements of these properties in a cone calorimeter [5]. A web of the particular cables to be simulated can readily be cut into appropriate lengths, mounted in the calorimeter and the heat release rate measured when the specimen is subjected to prescribed levels of external radiant heating.

Figure 1 illustrates such data for a polypropylene, zero-halogen cable, supplied by Borealis [6], at three levels of irradiance - 20, 35 and 50 kW/m². The time-dependent rate of heat release of the planar web of 10 cm lengths of cable (each 8.5mm in diameter) has a relatively consistent profile, distinguished from each other by the time-to-ignition and the general levels of heat release. At an incident flux of 20 kW/m² the ignition of the sample is clearly marginal, taking in excess of 20 minutes and exhibiting considerable variability.

The strategy to be adopted in the simulations is to incorporate the measured time history of mass loss rate directly into the computations, selecting the time-to-ignition for each discretised cable element on the basis of the cumulative heat flux to that element. The particular heat release profile is then selected to be that corresponding to the heat flux level prevailing at the time of ignition.

If the surface of an infinitely thick solid is heated at a constant rate, Q , the temporal variation of the surface temperature, $T_s(t)$, is given by

$$T_s(t) - T_0 = \sqrt{\frac{4}{\pi \rho c k}} Q t^{1/2} \quad (1)$$

where T_0 denotes the initial surface temperature and ρ , c , k are the material properties of density, heat capacity and thermal conductivity respectively [7].

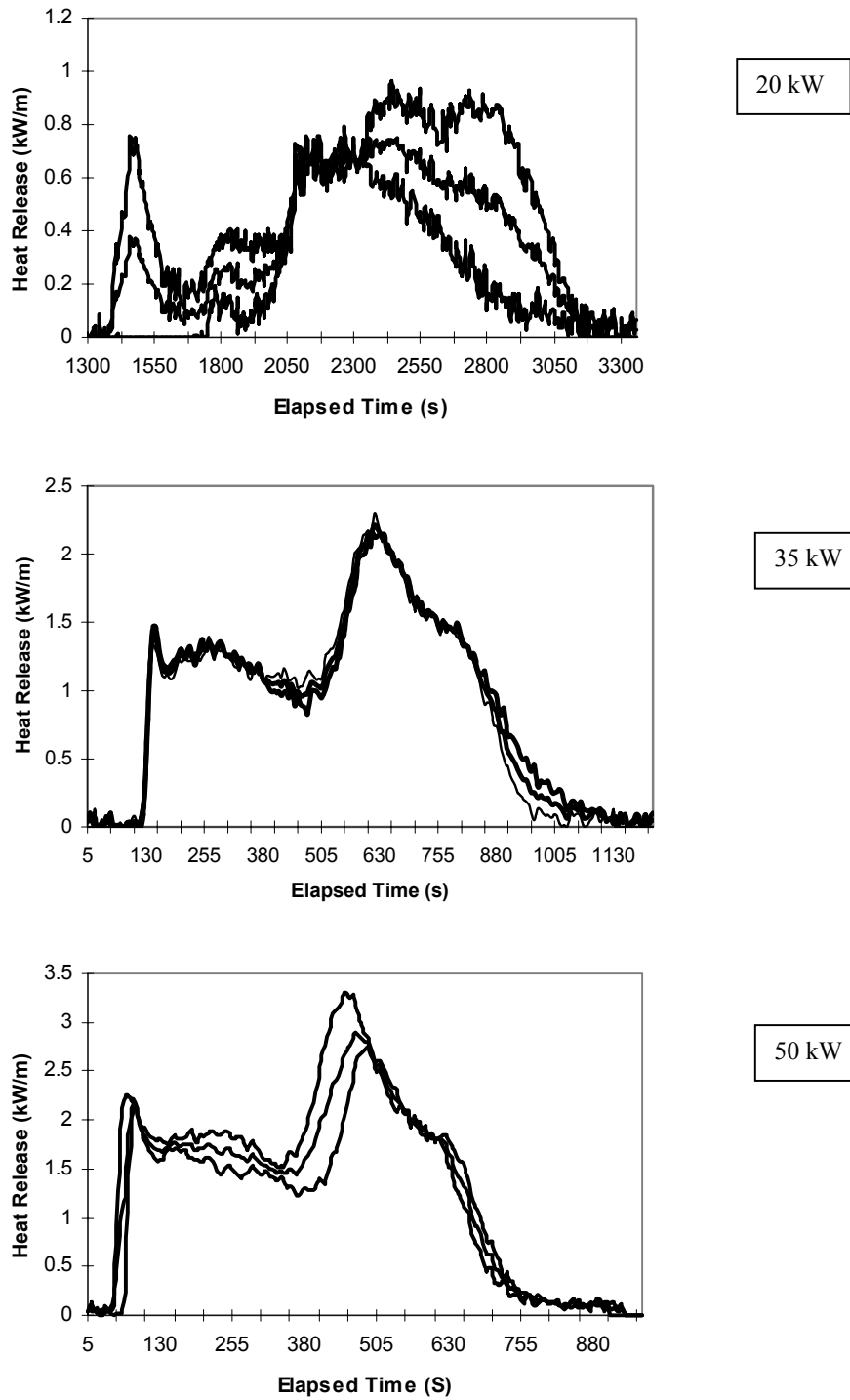


Figure 1. Cone calorimeter data for a polypropylene, zero-halogen cable

If we suppose that devolatilisation of the solid material begins at a prescribed temperature T_S then equation (1) suggests that an effective ignition criterion might be expected to take the form

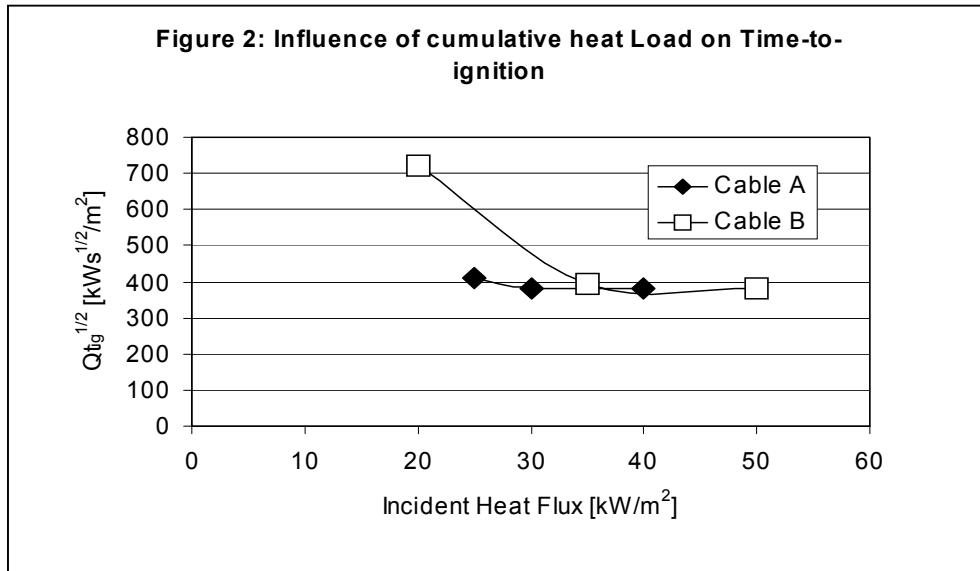
$$Qt_{ign}^{1/2} = \text{constant} \quad (2)$$

Figure 2 illustrates the application of this criterion to the cone calorimeter data of fig1. These are supplemented by additional cable data taken from Gandhi et al [8]. With the exception of the Borealis data at the lowest cone heating rate - identified as delayed marginal ignition - the criterion appears to be reasonably well-founded.

In the simulated (and any practical) cable fire scenario the heat flux to a surface element is not constant, however, and the expression in eqn.(2) has therefore been modified to take the form of an integrated property such that

$$\int_0^{t_{ign}} \frac{1}{2} Q(t) t^{-1/2} dt = \text{constant} \quad (3)$$

which reduces to Equation (2) when Q is constant.



Once this criterion has been satisfied and ignition is considered to have occurred, the subsequent, time-varying, rate of heat release is assumed to follow the profile corresponding to cone data at the local irradiance prevailing at the time of ignition (cf. Figure 1). Intermediate conditions are simply interpolated from those measured. Clearly, once the specimen is ignited in the cone calorimeter experiment, the incident heat flux

includes contributions from the burning pyrolysate in addition to that from the radiant heater. The approach implies that these additional contributions are broadly comparable in the cone experiment and the simulated flame spread scenario. In the absence of detailed measurements of the actual heat flux to the specimen surface during the cone calorimeter experiment, it is difficult to assess the influence of this simplifying assumption. A more significant aspect of the cumulative time-to-ignition model is that the criterion will eventually be satisfied irrespective of the level of heating, however. A second criterion is therefore introduced requiring that the incident heat flux at the point of ignition, or at any time thereafter, exceed the marginal level of 25 kW/m^2 . This implies that ignition is delayed, beyond the threshold criterion, at low heat fluxes and that burning may be extinguished if the heat flux falls to a low level subsequently in the simulation. This latter condition might be expected to arise as the flame spreads vertically, when some lower parts of the cable may be completely consumed and the influence of any pilot flame diminishes – as in the standard test (IEC 61034-2, for example).

Since the flame spread simulation includes detailed computation of the gas phase, the cable rate of heat release is itself of rather limited value and has been converted to an equivalent gaseous hydrocarbon mass flux. In the present illustration, the pyrolysate is assumed to be ethylene, which is then consumed in the gas phase combustion model, and coupled to the heat transfer computation, in the usual way [1]. It would be possible similarly to compute the smoke yield [2], but in the absence of detailed measurements of soot concentration such predictions could not be evaluated. Soot does, however, contribute to the radiative exchange, which is included in the simulation, and to this end a simple fractional yield of 2% by mass was introduced [3].

Further discussion of the model is deferred to the discussion of the results of simulation.

RESULTS AND DISCUSSION

Flame spread scenario

As part of an investigation of cable installation practice on fire performance, Robinson and Samson [9] report a pronounced sensitivity in some of their experiments to support tray geometry and, in particular, to sidewall depth. Though the primary objective of the present study is to demonstrate methodology in relation to cable fire simulation, CFD is particularly well-suited to the task of evaluating the interaction between fire development, materials and installation. The configuration simulated here is therefore taken from one of their experiments and comprises 1.5m lengths of cable installed as a flat web and mounted vertically in an open rack. The fire spread is piloted by a standard alcohol burner mounted at the base of the cable tray as prescribed in the test method IEC-61034.

Some further simplification of this arrangement has been introduced in order to emphasise the cable flame spread aspects. The pilot burner, with a mean output of 12kW,

corresponding to the steady consumption of 1 litre of ethanol over a 30 minute period, was replaced by an equivalent gas burner fuelled by ethylene. The cable tray investigated experimentally comprised a metal channel incorporating a fairly elaborate pattern of perforations. In addition to assisting assembly these holes also influence local ventilation, especially when the tray is not flush-mounted against a wall. In the numerical simulations, the pattern of holes was reduced to a pair of longitudinal slots - one in the tray base, between the cable specimen and the sidewall, and a second along the sidewall itself. The configuration is illustrated in fig. 3. In a further set of simulations the sidewall has been substantially reduced (from 60 mm depth to only 8.3 mm). The web of cables is represented as a single rectangular slab that defines the material surface on which net heat fluxes are computed and from which mass is lost. The fine detail of cable pyrolysis is considered to be embedded entirely in the cone calorimeter data. Given the plane symmetry of the configuration, the computational mesh employed incorporates a plane of symmetry along the tray centreline to introduce better spatial resolution within the overall mesh budget (80,000 cells).

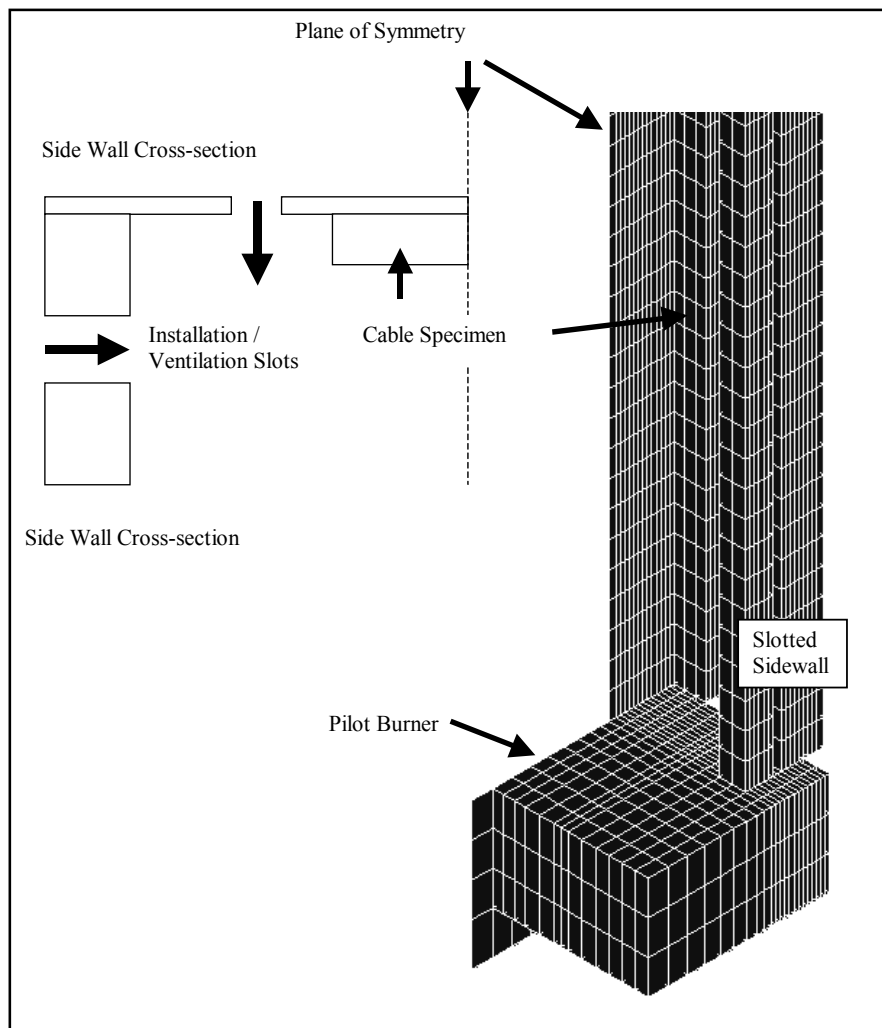


Figure 3 : Computational Mesh for 60mm Sidewall Tray

Fire simulations

Figures 4 and 5 illustrate the development of the flowfield within the 60 mm sidewall tray in vertical and cross-flow planes. The flow in the channel mid-plane is strongly accelerated immediately above the pilot burner, suggesting high levels of both convective and radiative heat transfer as the flame is drawn towards the cable specimen. The flow pattern in the cross-stream plane illustrated in fig.5, at a height of 12cm, reveals that there is substantial inhomogeneity in the space between the cable and the sidewall. The inflow through the installation slots has a marked impact on the position of the burning zone, preventing the burnt gases from simply spilling into that space. The accompanying heat fluxes along the web mid-plane are illustrated in figs.6(a-c) at discrete times throughout the development of the fire. The negative fluxes from non-burning parts of the cable, both convective and radiative, reflect the assumption that the surface temperature is fixed arbitrarily at 600K. Such an assumption is made necessary since no calculation is performed of heat transfer within the solid when the mass loss rate is controlled solely by the computed incident heat flux and the cone calorimeter data on rate of heat release. The total surface heat flux (fig.6c) peaks at approximately 45 kW/m^2 in the region where there are substantial contributions from both the pilot burner and the cable specimen. The distribution after 10 seconds – before the specimen is significantly engaged – indicates that the pilot burner contributes to surface heating over approximately 15cm of the cable.

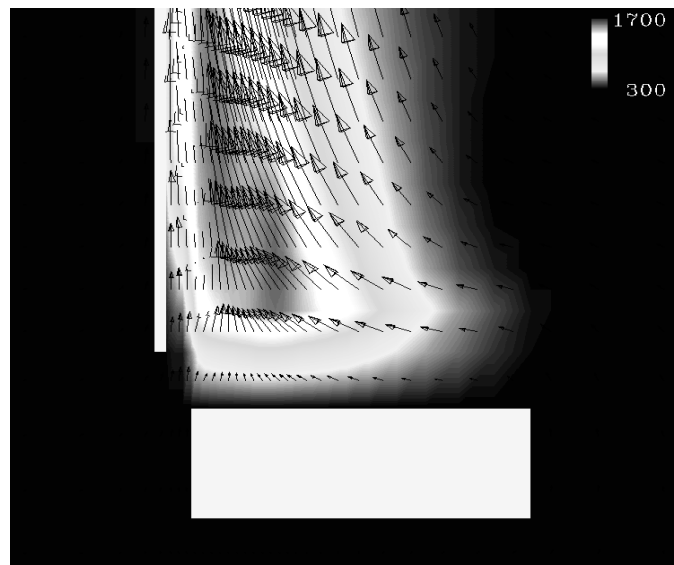


Figure 4: Side view of the velocity and temperature distributions in the tray mid-plane

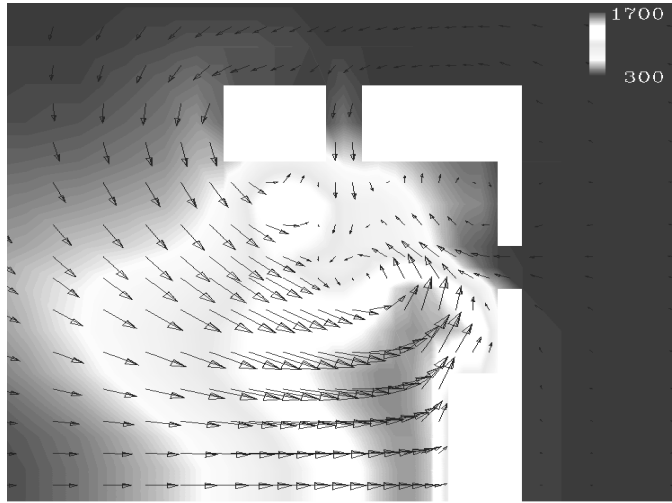
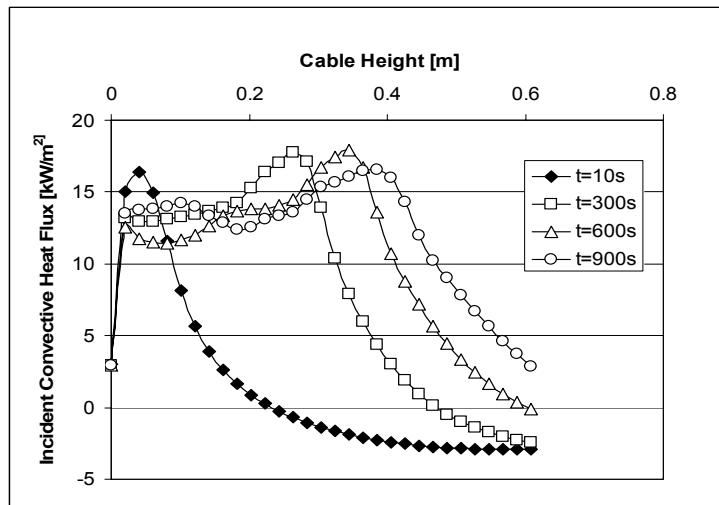


Figure 5: Cross-section of the tray : horizontal velocity and temperature distributions

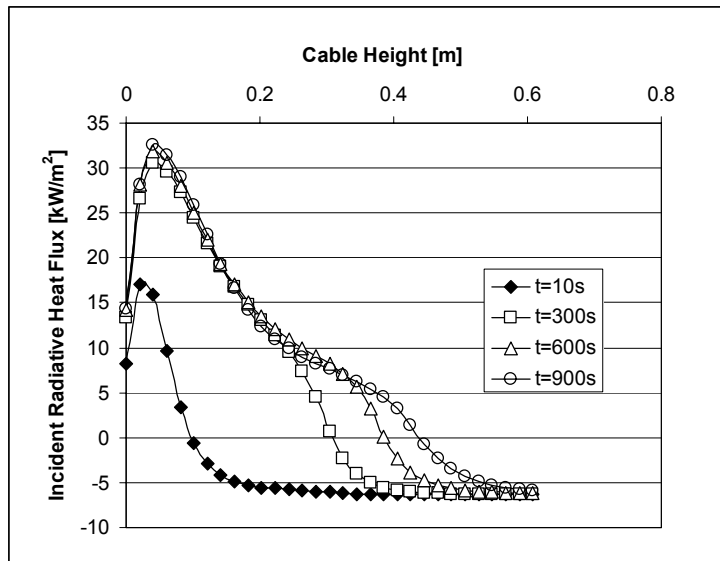
The cone calorimeter measurements in fig.1 indicate that the cable specimen burns for approximately 900s before it is entirely consumed. The simulated heat flux distributions in figs.6(a-c) corresponding to this elapsed time should not therefore show any significant effects of burn-out, even at the lower cable heights that were engaged first. However, though the heating of the cable continues to be progressive, the total flux (fig.6(c)) at heights above 20cm declines slowly with time and beyond 30cm falls below the threshold level of 25kW/m^2 . No fresh surface elements are therefore engaged beyond this height. Whilst the precise threshold level is somewhat arbitrary, the trend of the solutions is clear and reducing the threshold to, say, 20kW/m^2 might be expected to only extend the burning to 40cm.

Figure 6 : Distribution of heat flux to mid-plane of cable specimen

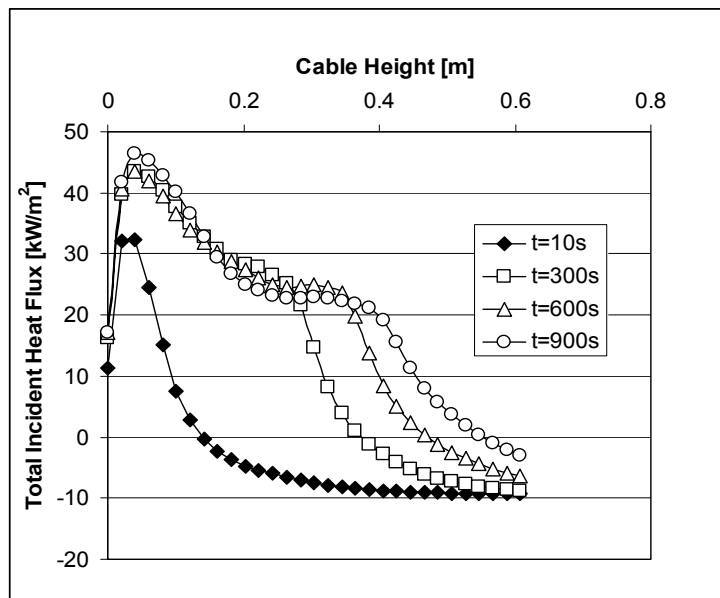
(a) Convective



(b) Net Radiative



(c) Total



A similar computation has also been performed for the cable tray with the very small (8.3mm) sidewall. Figure 7 illustrates the cross-stream temperature and velocity distributions again at the 12cm cable height station. The entrained inflow is now very pronounced and the high temperatures are restricted to the immediate neighbourhood of the cable specimen.

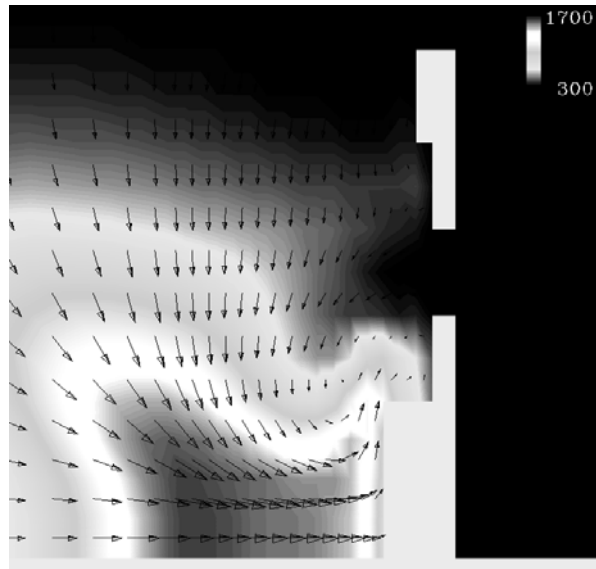
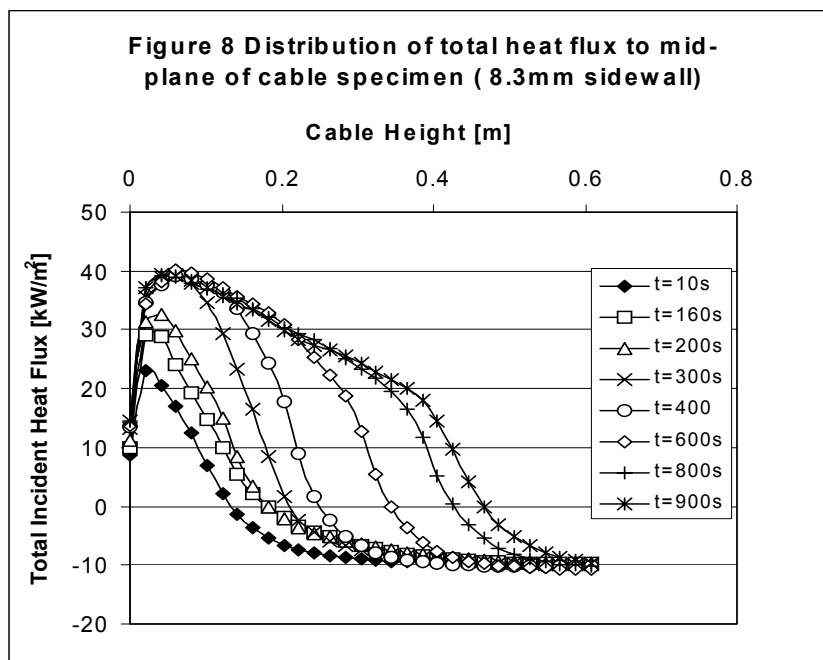


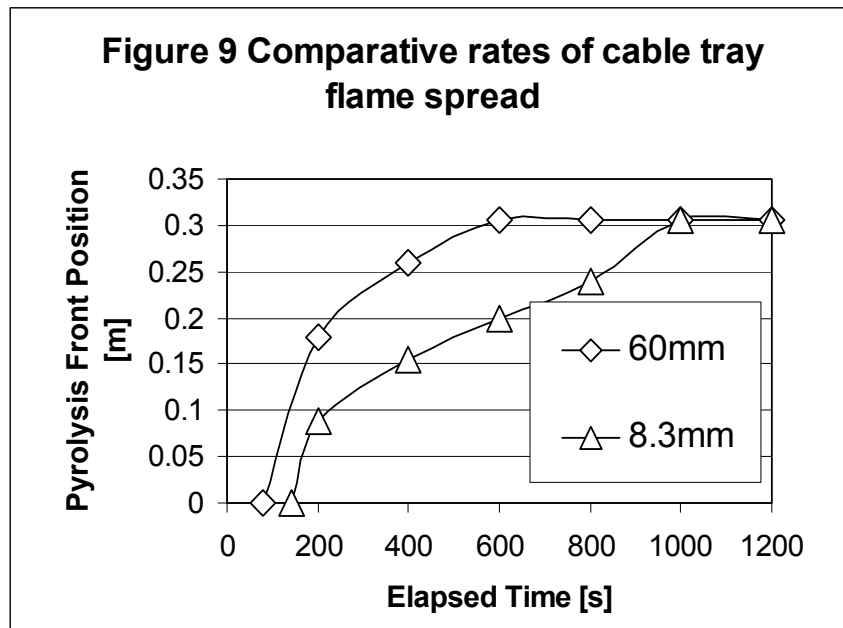
Figure 7: Cross-section of the 8.3mm tray: horizontal velocity and temperature distribution at a cable height of 12cm.

The accompanying total heat flux - time history is shown in fig.8. Peak levels at the base of the specimen are reduced by roughly 15%, in comparison with those predicted in the case of the 60mm sidewall tray, and the surface ignition is correspondingly delayed. The general trend is similar, however, to that observed in the earlier scenario.



Whilst the early growth of the fire is clearly revealed in the profiles of heat flux to the cable specimen, the development beyond 600s is inhibited and at approximately 30cm height the flux falls below the 25kW threshold.

Using the triggering of surface mass loss, by the criterion in eqn.(3), as a measure of the spread of the pyrolysis front we can compare the sensitivities to tray sidewall height indicated in the two simulations. Figure 9 illustrates this comparison. The key difference between the simulations lies entirely in the initial development.



Discussion

The preceding computations are not intended to provide a detailed quantitative analysis of specific cable fire measurements. The model proposed contains a number of assumptions that cannot be readily established from existing data, whilst the tray geometry is perhaps unreasonably over-simplified. These are not overwhelming obstacles, however, and therefore some review of the several model components is appropriate here. Measurements as part of the investigation in [9] which most closely resemble the configurations simulated here (sidewall heights of 60mm and 5mm) indicate fire damage to heights of 46cm and 36cm respectively. Greater numbers of cables, whether in webs or bundles, are reported to produce damage up to 1m in height. Given the empirical nature of the pyrolysis model, the level of agreement between experimental observation and simulation is unsurprising but also quite encouraging. Whilst the isolated cable tray fire test is not an elaborate, large scale fire scenario, it might reasonably be considered to be an element or module in such

Given the diversity of materials employed in the built environment, the numerical simulation of fire scenarios will continue to rely on laboratory test data for representations of small-scale processes occurring within the solid. The key to improving these models is therefore to improve our understanding of the test methods. From this

perspective the cone calorimeter is a powerful, but incompletely characterised, tool. The notions of time-to-ignition and self-extinction appear to be well-founded, but the reliability with which such values may be cited and the implications of any particular assumption within a more elaborate scenario is uncertain. The 20kW irradiance employed in fig.1 is clearly a marginal case, leading to a 20 minute ignition delay in one case and an almost 30 minute delay in another. Once the cable specimen has ignited, however, by how much is the surface heating augmented by the surmounting flame and is it primarily radiative or convective? If the net flux - radiant heater and flaming combustion products - is now reduced to 20kW/ m², is the specimen extinguished?

The extent to which highly localised burning in the fire simulation can be satisfactorily represented by the heat release rate inferred from the cone calorimeter is unclear without more analysis of the test procedure. Considerable refinement of the present CFD representation is possible, however, before the computational burden becomes comparable with that of computing heat and mass transfer and pyrolysis chemistry within a thin composite solid.

CONCLUSIONS

A methodology is described for the CFD-based simulation of fire spread along cables mounted in trays. The pyrolysis of the solid is described in terms of a rate of mass loss inferred from cone calorimeter measurements. Both rates of flame spread and the extent of propagation observed experimentally are plausibly reproduced.

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