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Application of Computational Fluid Dynamics modelling in the process of forensic fire investigation: Problems and solutions

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Abstract

Fire modelling has been gaining more and more interest into the community of forensic fire investigation. Despite an attractiveness that is partially justified, the application of fire models in that field of investigation rises some difficulties. Therefore, the understanding of the basic principles of the two main categories of fire models, the knowledge of their effective potential and their limitations are crucial for a valid and reliable application in forensic science.

The present article gives an overview of the principle and basics that characterise the two kinds of fire models: zone models and field models. Whereas the first ones are developed on the basis of mathematical relation from empirical observations, such as stratification of fluid zones, and give a relatively broad view of mass and energy exchanges in an enclosure, the latter are based on fundamentals of fluid mechanics and represent the application of Computational Fluid Dynamics (CFD) to fire scenarii. Consequently, the data that are obtained from these two categories of fire models differ in nature, quality and quantity.

First used in a fire safety perspective, fire models are not easily applied to assess parts of forensic fire investigation. A suggestion is proposed for the role of fire modelling in this domain of competence: a new tool for the evaluation of alternative hypotheses of origin and cause by considering the dynamic development of the fire. An example of a real case where such an approach was followed is explained and the evaluation of the obtained results comparing to traces revealed during the on-site investigation is enlightened.

Keywords: Forensic science; Fire modelling; Field models; Hypothesis evaluation; Results interpretation

1. Introduction

Fire investigation, as it is traditionally undertaken, consists in the search for traces and their scientific evaluation in order to determine two ‘‘static’’ parameters that explain the start of the fire. First, the on-site investigation has to delimitate the origin of the fire, representing the location of the initial seat of the fire. Then a systematic and scientific methodology must be applied in order to establish the cause of the fire. The latter assumes an evaluation of the combustible that was first involved and, most of all, a determination of the nature of the heat source that allowed the start of the fire.

In some cases, the investigation needs to study the dynamic aspect of a fire: its development, its propagation from the initial flaming to its final extent, considering both the spatial and time evolutions of the phenomenon. These aspects are generally apprehended by collecting and analyzing testimonies and by reconstructing a chronology of the event. Despite providing a precious help in the evaluation of the possible scenarii of cause of the fire, such an approach is not sufficient to assess a conjecture of fire propagation arising from the fire investigation or to discriminate between two or more alternative hypotheses of cause of the fire.

The evolution of computer science in the past decades has brought a decisive improvement in calculation capacities allowing the set up of systems able to tackle very complex integrations of mathematical relations [1]. Among them, one specific development has had a great impact on the study of the dynamic evolution of fires: fire modelling. First developed for fire safety studies, so-called zone models and field models have been sporadically used in a more ‘‘forensic’’ way since the beginning of the 90s, with their first major applications being

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most probably for the explanation of the 62 Watts Street Fire in New York (March 28, 1994) [2] and the King's Cross Station Fire in London (November 18, 1987) [3–8].

In the first part of this paper, a brief description of the two different kinds of fire models will be presented. This will be followed by a proposition of use of fire modelling in a forensic fire investigation process, illustrated by an example of application. Finally, a reflexion of the role and the future of fire modelling in forensic sciences will be proposed as a concluding part.

2. Computer fire models

Two large categories of fire modelling systems based on computer calculations are to be distinguished: the *zone models* and the *field models*. They differ by the general approach on which they are based.

2.1. Zone models

As clearly mentioned by Walton, "Zone fire models are computer programs designed to predict the conditions resulting from a fire in an enclosure" [9]. The zone models are built on the assumption that corresponds to an empirical recurrent observation of fire happening in enclosures. As the fire grows, the hot products of combustion are entrained in the plume of the fire in the upper part of the enclosure under the influence of convection flows. In a macroscopic point of view, a zone containing the hot gases and chemical species produced during the combustion invades the upper part of the environment as a cooler zone, free of smoke and soot, remains in the lower part; a stratification occurs in the enclosure where these two regions can be clearly distinguished. The zone models consist of mathematical relations applied to this empirical statement. The volume of the enclosure on which calculations are conducted, called *computational environment*, is divided in large homogenous regions. Four different zones are generally distinguished although more can be specified: the fire, the plume, the hot upper zone and the cold lower zone. The fire is considered as a volumetric source of heat and species; it is therefore described by heat and mass release rates. The heat and species produced are entrained by the plume, which acts like a pump, into the hot upper zone, whereas the cold lower zone remains close in property and composition to fresh air. Into each zone, the temperature and the concentration of the different chemical species are considered spatially uniform but vary with time. After discretisation, the system of equations that constitutes the core of a zone model is solved by computing resources; the time evolution of the different variables in a given zone and the flows of energy and mass between two adjacent zones are then calculated [10–12].

Due to their relative simplicity and the empirical assumption of stratification on which they rely, zone models suffer from consequent limitations. Many of them were discussed in the past [13,14], enlightening the risk of obtaining non-valid or even non-realistic results for certain geometrical configurations. But among all limitations, the major one consists most probably in the requirement for an a priori knowledge of the structure of the flows that will take place in a given environment [15]. Since zone models rely on very constringent empirical assumptions, it must be assessed that the geometry and the configuration submitted to the model fulfil these assumptions. In a very pragmatic way, this limitation involves that a scientifically valid application of zone models cannot be carried out independently of scale or real size experiments.

2.2. Field models

The only characteristic that field models share in common with zone models relies in the use of computer systems for the solving of a set of equations that describe time and space evolution of scalars and flows in a given volume. For all other aspects, field models differ significantly. Instead of being separated in large homogenous zones, the environment is divided in a large amount of small cells which size must be related to the combination of geometric complexity, time discretisation and the magnitude of flows passing through opponent faces of the cell. The complete arrangement of cells composes the computational environment and is usually described as *mesh* or *grid*. On the basis of this mesh, the fluid flows induced by a fire are calculated by applying the basic equations of fluid dynamics, generally known as Navier-Stokes equations. These equations establish the balance of flows for each cell of the environment: the flows entering and leaving the cell, the residence time of flows in the cell, the rate of creation and destruction of flows in the cell are considered. The application of such equations describing fluid dynamics into models that solved them by means of computer is generally known as Computational Fluid Dynamics (CFD) [16–18]; field models correspond to the application of CFD codes to the simulation of fire scenarii. The principle of ascertaining a balance by means of computational calculations seems quite similar to the approach of zone models. But since the space discretisation is much finer, the number of distinguished volumes composing the complete environment is far greater and thus the data for heat and mass transfers are much more informative. With such an approach, the transfer of mass and energy that takes place by convection can be quite precisely calculated. The integration of other heat transfer mechanisms involved in a fire, conduction and most of all radiation, requires the set up of a parallel application of sub-models that interact with the core model of fluid dynamics [19,20]. Moreover, other sub-models must be integrated to take account of other phenomena that cannot be correctly represented with the core model, such as turbulence, which is often simulated with the k–ε model [19,21,22].

The application of CFD requires the delimitation of the environment on which calculations are performed. The computational environment is thus not a infinite medium and therefore boundary conditions must be applied to its limits as well as to each location where a geometrical discontinuity appears, such as walls or apertures. These boundary conditions refer to routines that guide the model in the calculations process at specific locations of the computational environment.