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Coupled hybrid modelling in fire safety engineering; a literature review

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ABSTRACT

Systems in the built environment are getting bigger and more complex. Fire safety engineers are required to analyse these structures to ensure acceptable levels of safety. Computational limitations mean that the calculation domain must be curtailed. This ignores the two-way coupling between the total system and a fire. Coupled hybrid modelling (coupling of fire dynamics sub-models with a range of computational costs) expands the domain and analyses this two-way coupling within a reasonable timeframe. This article presents a literature review of this modelling paradigm and has application for those investigating and expanding the method.

Over the last quarter of a century, researchers have investigated coupled hybrid modelling but work has been in disconnected streams. There has been no review of coupled hybrid modelling for fire safety engineering. It is unclear where the knowledge gaps are and where future work should be focused.

This review demonstrates that the method is numerically feasible and can reduce wall clock time for total system analysis. This review reveals that there is limited validation and a host of unresolved questions (including sub-model choice, interface modelling, domain decomposition and coupling method). This review draws attention to the lack of collaboration which has led to obsolete models and parallel working.

This article shows that coupled hybrid modelling has potential but effort is being squandered. This review is a stepping-stone towards a standardised coupled hybrid framework. This review highlights where future collaborative research should be directed.

1. Introduction

1.1. Problem

The construction industry is driven by time constraints [1] and these constraints can lead to compromises in engineered safety [2]. As with other fields, this is true for fire safety engineers, designers and modellers. To deliver output within reasonable and expected timeframes, modellers curtail the domain to keep simulation runtimes low [3,4]; as shown in Fig. 1. Modellers explicitly consider a small part of a total system (e.g. a single room in a building or a short section of a tunnel) and expand conclusions to the entire system [5].

Over half of fire fatalities in the built environment in the US, UK and Australia occur outside of the room of fire origin [6–8]. Over 65% of UK fire fatalities are due to smoke inhalation [9]. The entire building system and its ventilation have significant influence on how fire behaves and how smoke is generated and spreads throughout system [10]. The current typical fire safety engineering modelling paradigm ignores this two-way interaction of the total system and the fire. The acuteness of this risk is increasing as buildings are getting taller [11] and more complex [12], tunnels are getting longer [13], and the whole built environment is becoming more reliant upon performance based design [14].

One of the solutions to address this issue is "coupled hybrid" modelling – coupling multiple sub-models, with the same function but with differing complexities and computational costs, into a single simulation tool (refer to Fig. 2). This coupled hybrid method enables modellers to expand the calculation domain and explicitly examine more, or all, of a total system [15,16].

1.1.1. What's in a name?

Coupled fluid modelling has been investigated in a wide range of fields of study (haemodynamics [17], indoor air quality [18], building ventilation [19], including fire [20], tunnel ventilation [21], including fire [22], wildland fire [23] and climatology [24]). Each field has slightly differing terminology for this method; including coupled, hybrid, integrated, multiscale, two-scale, multi-dimensional, 3D-1D, field-zone, field-network and others. In this review, we adopt the catch all term "coupled hybrid" to describe the coupling of two or more sub-models (which have the same overarching function) into a single hybrid model. It is acknowledged that some coupled hybrid models may also be multiscale (work at multiple scales of time and space), 3D-1D

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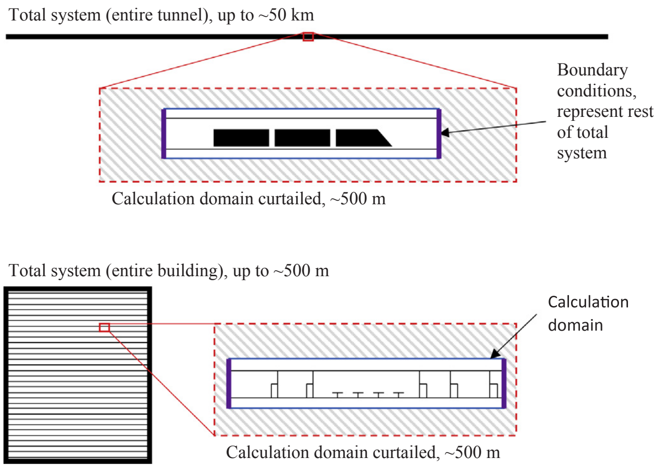

Fig. 1. Typical fire safety engineering modelling paradigm.

(couple 3D and 1D fluid solvers), field-zone (couple a field model and a zone model), etc.

1.1.2. Modelling methods for fire and smoke

Here we present a short description of the model types discussed in this review (refer to Fig. 3 for an illustration of the model types). The definitions are not designed to be comprehensive explanations but instead to give a broad overview and to point those interested to further reading. The models are presented in order of increasing complexity and computational cost.

1D network models represent a system as a one-dimensional network of nodes (compartments or junctions) and node connections (ducts, tunnels, corridors or leakage paths). Nodes contain a single set of variables such as temperature, density, mass and are treated as homogeneous. Node connections represent 1D transfer conduits between nodes. Network models contain relatively simple forms of conservation equations such as the use of Bernoulli's equation for the conservation of momentum and hence enable a large domain to be analysed with low computational cost [25]. Examples of network models include the Subway Environmental Simulator (SES) [26] and Fire and Smoke Simulator (FSSIM) [25].

Zone models represent a compartment as multiple uniform zones (typically two zones: a hot upper layer and a cooler lower layer) with the inclusion of vents to represent doors and windows [27]. Zone models solve conservation equations between the uniform zones and typically include empirical relationships for phenomena such as fires, plume flow and corridor jets. Zone models are limited by the geometry they can represent (simple, cuboidal compartments) but are solved relatively quickly. Examples of zone models include CFAST [28] and BRANZFIRE [29].

Field models, also called computational fluid dynamics (CFD) models, divide a domain into finite elements or volumes for which conservation equations are solved. Each finite element holds a set of conserved variables. Field models can be used to examine complex geometry but require large storage space, high computation requirements and have a high computational cost. Due to typical meshing strategies, field models are not well suited to studying leakage through small gaps in a relatively large enclosure [30]. Examples of field models include FDS [31], SMARTFIRE [32] and FireFOAM [33].

The term “coupled modelling” is sometimes also used in fire science to describe the coupling of field models and solid-phase heat transfer and structural response models [34,35]. These are not considered to be “hybrid” models (the sub-models do not perform essentially the same function) and are outside of the scope of this review.

2. Coupled hybrid modelling in other fields

The haemodynamics industry have employed coupled 3D-1D hybrid fluid models to simulate multiscale blood flow through vessels [17,36–41]. Coupled hybrid modelling in haemodynamics also incorporates unsteady geometric deformation of the vessel; typically via the use of FEM [42].

The automotive industry use coupled 3D-1D hybrid fluid and combustion models to simulate internal combustion engines [43–46]. Coupled hybrid methods enable the entire system, including combustion chamber, fuel injection, exhaust, intake and filters to be efficiently modelled. The method is used especially during engine development stage. 1D models typically used to simulate whole engine behaviour are phenomenological and require fitting to experimental data. To address the lack of validation data, 3D fluid models are used to capture complex combustion processes and pollutant generation [47].

Tunnel ventilation researchers and practitioners have developed and used coupled 3D-1D hybrid models for the “multi-dimension” design and assessment of ventilation systems and passenger comfort and safety [21,48–50]. In this industry the use of 1D network models to design ventilation systems is typical [26,51]. However, calculation of 1D junction loss factors is slow and labour intensive [52] and the required oversimplification of complex geometries at stations could introduce passenger comfort and safety risks [53].

The field of building simulation (the study of ventilation and air quality in buildings) use coupled hybrid modelling – these instances involve the coupling of a “multizone model” (a 1D network model) and a field model [19,54–60]. In building simulation, the field sub-model is typically used to simulate external wind conditions around the building and not features inside the building.

Wildland fire researchers use coupled hybrid methods, typically called atmosphere-fire coupling, to examine the interaction of wildfire and atmospheric systems [23,61–63]. Studies couple a field model (used to simulate mass and enthalpy flow in the atmosphere above a wildfire) and an empirical 2D fire spread model. The fire spread model provides a source of enthalpy to the atmosphere field model which then models large scale atmospheric flow and turbulence with a grid cell size of typically 20–100 m.

3. Coupled hybrid modelling in fire safety engineering

In fire safety engineering, coupled hybrid modelling can be broken into three categories based on the selection of sub-models. The categories are coupled field-zone, field-network and zone-network hybrid models. The following sub-sections provide a literature review for each category in turn.

3.1. Coupled field-zone hybrid models

The earliest of the coupled hybrid model categories to emerge. These models are used to examine building and ship fires. These coupled hybrid models simulate the fire, the enclosure of fire origin and proximal enclosures in the field sub-domain and simulate medium to far field spaces in the zone sub-model. Refer to Fig. 4.

Xu et al. [64] developed a coupled field-zone hybrid model and documented the results of a numerical demonstration case on a single storey, multi-room building. The field sub-model was 2D and was coupled to a bespoke zone sub-model. No validation of the coupled hybrid model was presented. Wang et al. [65] later extended the field sub-model to enable the consideration of 3D cases – the article is not scientifically thorough and presents a short summary of the extended model with no verification or validation.

Fan et al. [66], from State Key Laboratory of Fire Science of China, presented a field-zone hybrid method, coupling proprietary unnamed sub-models to create a new model called F-Z model. The field model used k-ε turbulence modelling. In the field sub-domain, the hybrid