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Experimental characterisation of two fully-developed enclosure fire regimes

A.H. Majdalani [a], J.E. Cadena [b], A. Cowlard [a,*], F. Munoz [b], J.L. Torero [c]

[a] *BRE Centre for Fire Safety Engineering, University of Edinburgh, UK*
[b] *Departamento de Ingenieria Quimica, Universidad de los Andes, Colombia*
[c] *School of Civil Engineering, University of Queensland, Australia*

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ABSTRACT

This work revisits the principle characteristics of two unique regimes of behaviour of fully-developed compartment fires first identified during the immense body of research that came to define the *compartment fire framework*. Experimentation and computational modelling are used to explore, compare and contrast the characteristics of these two Regimes and identify the transition or break point between the two. Their relevance to the design of contemporary infrastructure and need for a greater understanding of both Regimes in this context is discussed.

1. Introduction

Large, open, flexible volumes saturated by light through multiple large openings has been considered a common element of mainstream architecture since as long ago as the 1920s [1,2]. Over the same period, fire safety practitioners pursued fire resistant compartmentalisation as a means of reducing fire spread in buildings, enabling safe egress and more effective intervention by the fire service. Architectural objectives have therefore been, for many years, at odds with classic fire safety strategies.

Significant effort has been devoted for more than 100 years to establish methods that assess performance of fire resistant partitions and structures. Since the late 19th century, furnace testing was undertaken as a means to classify 'fire resistant' construction with a view to guaranteeing both compartmentalisation and structural performance in the event of a fire. Bisby et al. [3] provide a comprehensive history of fire resistance testing. Standardisation of this approach came about in the early 20th century, bequeathing a standardised fire environment, the standard temperature-time curve [4]. Further work to refine and rationalise this approach resulted in the concept of fire resistance ratings [5]. While furnace testing has some scientific basis, the current practise of using furnace testing as the basis for structural fire resistance classification remains questionable.

An impetus to provide more explicit descriptions of the fire environment to enable better engineered structures emerged in the 1950s and continued until the 1990s. A detailed description of this immense body of research, dubbed the *compartment fire framework,* is presented by Majdalani [6] and the general conclusions summarized by Torero et al. [7].

The *compartment fire framework* still remains the foundation of our knowledge of enclosure fire dynamics and of the engineering tools subsequently derived. Nevertheless, the problem of how to quantify the thermal load imposed by a fire on a structural system is far from resolved. As explained by Torero et al. [7], the experimental studies used to define the framework lack diagnostic resolution and are not necessarily of a parametric nature therefore have left the description of the fire environment and the different regimes observed incomplete. Computational tools have the capacity to fill the necessary gaps of knowledge; nevertheless, in the absence of detailed experimental data, their validation within the fully-developed regimes remains unsatisfactory. If the existing engineering tools or modern computational tools are to be used to provide explicit representations of the thermal loads imposed to a structure during a fully-developed fire it is of great importance to have better resolved descriptions of enclosure fires and their evolution as the enclosure disappears to give way to modern architectural spaces. This paper initiates the process of further resolving enclosure fires by experimentally revisiting the different regimes using modern experimental techniques supported by simple computations.

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[*] Corresponding author.
E-mail address: adam@taec.engineering (A. Cowlard).

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1.1. *Benchmark breakthroughs in compartment fire dynamics*

The effects of confinement on burning rate are first reported by Kawagoe [8] and Kawagoe and Sekine [9], following previous work by Fujita [10] who investigated methods to establish fire duration and by extension, fire severity. These works are the first to identify the proportionality of burning rate, *R*, and a ventilation factor ($A_w\sqrt{H}$), where A_W is the area of the openings of a compartment and *H* the height of the openings. Kawagoe [8] is thus the first to formally establish the concept of the compartment fire by coupling compartment characteristics and burning rate. These findings are further corroborated and extended by others [11,12,13].

In the early 1960s, studies by Thomas et al. [14,15], and Thomas [16,17,18] concluded that there were *at least two* regimes of behaviour in the fully-developed stage of compartment fires [19] i.e. full room involvement in which all exposed combustible surfaces are burning. Thomas et al. [14] observe that at low airflows, the rate of burning, *R*, has a linear dependency on the airflow, in agreement with Kawagoe [8], Kawagoe et al. [9] and Fujita [10]. However contrary, at high airflows, the burning rate reaches a constant value which appears proportional to the surface area of the fuel, A_f. These distinct behaviours, identified as *Regime I*, the low ventilation regime, and *Regime II*, the high ventilation regime, are described here.

1.1.1. *Regime I*

A *Regime I*, or window controlled fire is a fully-developed compartment fire where the opening vent is small, and thus the average rate of burning, *R*, inside the compartment is determined by the size and geometry of the vent. This corresponds to the scenario originally described in [8] and [9]. The gas phase is characterised as 'well stirred' (i.e. uniformly hot) and relatively still within the enclosure and air inflow and gas outflow driven by the pressure difference between the uniformly hot interior and uniformly cold ambient exterior. Velocities are mainly horizontal and confined to the region of the opening (Fig. 1a). Small openings result in a large portion of the energy produced by the fire remaining within the compartment, thus overall compartment temperatures are expected to be high and heat transfer to the boundaries spatially uniform.

1.1.2. *Regime II*

A *Regime II*, or fuel surface area controlled fire is also a fully-developed compartment fire but large openings mean that there is ample air supply thus the rate of burning inside the compartment is controlled by the fuel surface size, location and distribution. An open compartment limits retention of a significant portion of the fire products, and consequently a hot, well stirred upper layer is not able to form and significant gas phase temperature gradients exist within the compartment. By extension, the stack driven flow does not form and air entrainment is instead governed by the fire plume itself. Horizontal flows are thus expected to accelerate in the vicinity of the fire plume boundary and develop a strong vertical component as gases are entrained into the rising plume (Fig. 1b). Gases will then flow across the ceiling and out of the opening. The open nature and high velocity flow regime result in a large portion of the energy produced by the fire flowing out of the compartment, thus the characteristic internal temperatures will be comparatively lower than those of a *Regime I* fire. The flow characteristics also mean that heat transfer to interior boundaries will not be spatially uniform.

1.2. *Thomas and Harmathy*

While a significant volume of theoretical and experimental studies exist for compartment characteristics relevant to *Regime I*, fundamental knowledge and research regarding *Regime II* compartments is relatively sparse. The significance of this disparity becomes apparent when considering the juxtaposition of a century of an architectural mainstream tending towards open, light-filled spaces while concurrently, fire research and fire safety strategies are conceived on the basis of compartmentalization.

A major reason behind this skewed focus stems from the philosophies of the leading researchers of the time, Philip Thomas and Tibor Harmathy, whose sometimes apparently contradictory opinions helped shape the resulting *compartment fire framework* and tools used in design to the present day. A comprehensive overview of Thomas and Harmathy's insights is given by Majdalani [6].

Thomas' opinion was that compartment fire dynamics as conceived of at the time, was only applicable for use in structural design [20]. Given the theoretically simpler nature of *Regime I*, coupled with typically higher temperatures, Thomas deemed design methodologies forcing compartmentalization, and thus accounting adequately for the associated increased temperatures as a more conservative and informed approach. At the same time however, Thomas promoted the need for a more comprehensive understanding of both Regimes.

Harmathy in contrast derided as myth the concept of a perfectly sealed fire compartment pointing to the architectural reality [21]. Further, Harmathy emphasizes how fire spreads by multiple mechanisms which are again more in-keeping with and relevant to real buildings [21,22,23]. Harmathy encouraged taking advantage of the *Regime II* characteristics, promoting the opening of compartments and the consequent reduced requirements for fire protection, and proposing methods for designing accordingly.

Seemingly, conservatism based on a greater theoretical foundation and a focus on structural design has resulted in the present

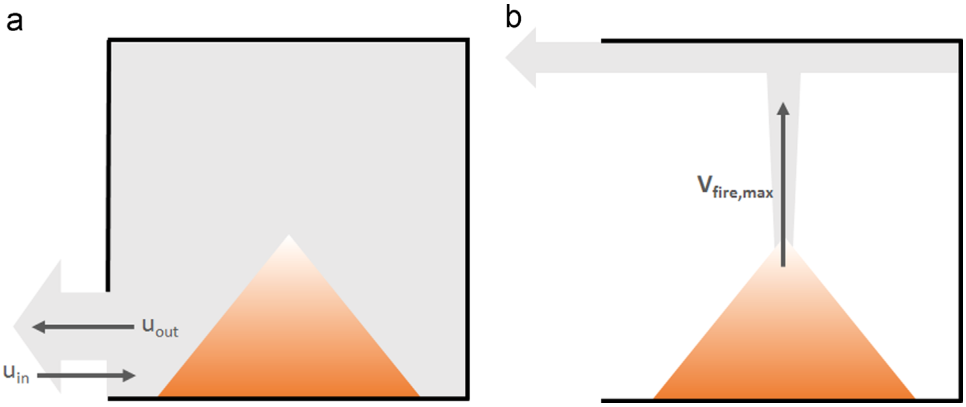

Fig. 1. The diagrams illustrate the characteristics, conditions and governing flows of (a) a *Regime I* and (b) a *Regime II* fully-developed compartment fire.