Influence of compartment geometry on internal flows in a fully-developed fire

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ABSTRACT

Contemporary architecture and new structural materials challenge the classical premise of fire safety: compartmentalisation. The historical classification between *Regime I* and *Regime II* is no longer sufficient to analyse the new fire behaviours we are encountering. This article presents an analysis of the impact of geometry on the development of flows in a compartment fire. The study contrasts the case of an almost cubic compartment with one that doubles its depth, using a CFD model. The model is validated using data from an experiment, where temperature fields were measured, and from which the flow fields are subsequently derived. Through computational models, the impact of the backwall effect on the magnitude and direction of velocities is observed. This effect increases velocity magnitudes by 35% and alters the flow direction. This article analyses the case of a cubic compartment and one with double the depth, examining how this variation affects flow development. The analysis was conducted using FDS simulations, validation the model with experimental data. Streamline plots reveal that in cubic compartments, the buoyancy of the flame does not directly influence the change in flow direction; instead, it is primarily due to the collision with the rear wall. Conversely, in the elongated case the fluid dynamics are significantly affected by the buoyancy of the fire plume, which deflects it toward the ceiling.

KEYWORDS: CFD, Fire Dynamics, Regimes of Behaviour, Compartment fire.

INTRODUCTION

Architecture in cities is evolving very quickly. Over the last decades, the construction of high-rise buildings has been characterised by the use of open-plan compartments, large windows (floor-to-ceiling), and timber as exposed structural material. The evolution of timber buildings can be observed in Fig.(1):

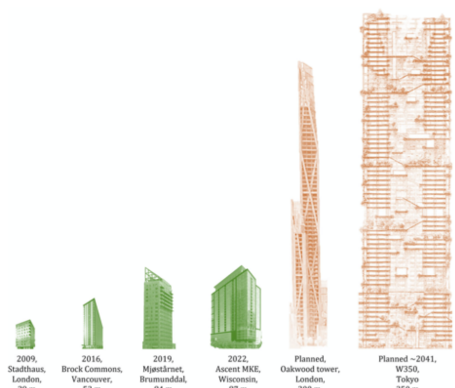


Fig. 1. Progression of the tallest completed and planned modern tall timber buildings. Obtained from [1]

These new aspects require that the *classic compartment fire framework* [2,3,4] be revisited, since many of its underlying assumptions have changed. Multiple series of experiments at different scales have been carried out to quantify the impact of exposed timber [5,6,7]. These experiments have produced valuable data related to temperatures, heat fluxes, and velocities at the opening. A few of the challenges of conducting experimental campaigns in timber structures is their high economic rates, and that they are time consuming.

A viable option to support this design process is the use of Computational Fluid Dynamics (CFD) methods. These allow for a more dynamic analysis of the fire behavior. The most commonly used tools are Fire Dynamics Simulator (FDS) [8] and FireFOAM [9]. Additionally, many simulations have been carried out using these to numerically reproduce experiments [10,11], validating these models. It has been shown, however, that predictive simulations of fire development are not possible [12]. This is due to the overly complex interaction between the different physical processes that govern fire growth, and the large uncertainties associated with the input parameters. Fig. (2) shows the predicted HRR for a compartment fire experiment. This is an example of the large uncertainty resulting from predictive fire growth simulations. Each curve is a different simulation for predicting the behavior of the same experiment, using a Round-Robin methodology.

Post-flashover or fully-developed fires were historically classified based on the relationship between the air inflow rate (indirectly related to the opening size) and the exposed fuel surface area. This ratio clearly defined 2 different regimes: the ventilation-controlled regime (namely *Regime I*) and the fuel-controlled regime (namely *Regime II*) [3]. During the fully-developed stage of a fire, when in *Regime I* behaviour, some variables related to the specific fuel load (movable fuel, e.g. furniture) are of less importance, like the overall HRR which can still be estimated based on the ventilation conditions given its dependency. Predictive numerical simulations of fire behaviour during this stage could, consequently, in principle be possible. For this, however, it is necessary to be able to reproduce the flow field inside the compartment correctly, which, in turn, requires capturing the underlying physical processes adequately.

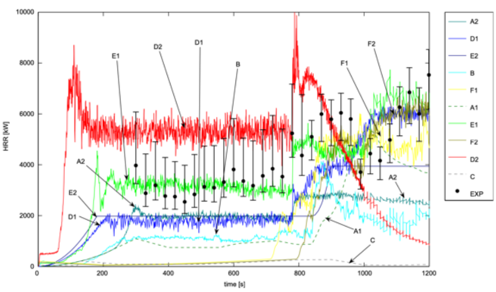


Fig. 2. Evolution of the HRR within the compartment. Obtained from [12]

In this paper the influence of the compartment depth can have on the internal flow field is studied numerically. For this, a fire in two compartments with different aspect ratios is simulated. This work focuses on CFD modeling of internal flows and how the compartment's geometry affects the fluid dynamics within it. Due to the lack of velocity data inside a compartment fire, a methodology is proposed in which, based on the validation of time-averaged thermocouple trees, the fluid behavior can be inferred.

Determining a velocity field from a temperature field alone is not entirely feasible, given that velocity and temperature are related through other factors in fluid dynamics, such as fluid pressure and density, but some characteristics of the field can be inferred. In systems where natural convection exists (e.g., fires), the currents transport heat from the source to the measuring points, and the time evoluciton of the temperature field can thus help estimate the velocity field, given that temperature differences cause density gradients and, in turn, buoyant forces that drive fluid motion.

To perform such estimations, CFD models are typically employed, which consider the conservation of mass, momentum, and energy. These models use the temperature field as an input to solve the velocity field along with other relevant parameters.

EXPERIMENTAL CAMPAIGN AND CFD MODELLING

This section presents the details of the experimental campaign carried out by Majdalani [13]. The small-scale compartment has internal dimensions of 0.82 m x 1.06 m x 0.82 m. A single constant width opening is included, which varies in 5 positions (100, 80, 60, 40 and 20 %). The walls and ceiling are made of ceramic fiber panels. Gas burners were used, consisting of a pipeline with 120 holes of 2 mm in diameter each, evenly distributed. To avoid the jet flame effect, the burner was inverted (pointing toward the floor) so as to obtain buoyant flames.

Three fuel mass flow rates were established (0.5, 1.0 and 1.5 g/s), which translates to heat release rates of 24, 48 and 72 kW per unit area. Table 1 below summarises all the experimental combinations.

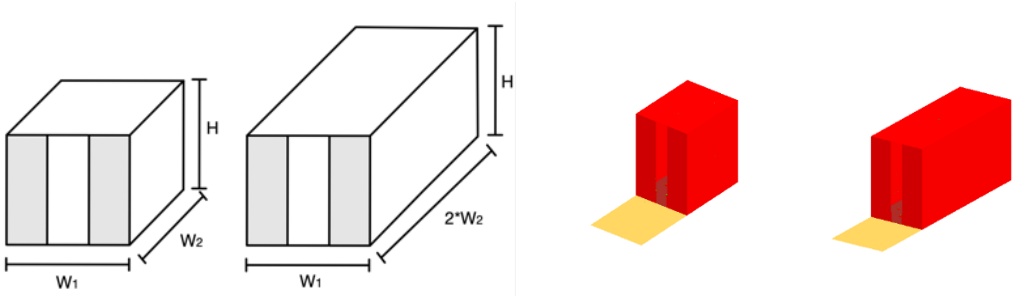
Table 1. Experimental cases according to gas flow and opening percentage.

Label	Opening (%)	Gas flow rates (g/s)	HRRPUA (kW/m^2)
Experiment 1	100		
Experiment 2	80	0.5	24 (small)
Experiment 3	60	1.0	48 (medium)
Experiment 4	40	1.5	72 (large)
Experiment 5	20		

Regarding the measuring devices, 54 thermocouples were placed on 9 trees at 6 different heights, 45 thin-skin calorimeters (TSC) distributed internally, and a maximum of 6 pressure probes at the opening.

The code used for the simulation was Fire Dynamics Simulator (FDSv6)[8]. FDS solves the Navier-Stokes equations adequate for low-speed thermally driven flows [10]. As Jahn et al. [10] explain, while large eddies are solved directly, turbulences at sub-grid scale are modelled using Smagorinsky's approach.

In order to analyse the flows in a traditional compartment, the experimental campaign conducted by Majdalani et al. [13] was simulated. In this same context, the present experimental data was used to validate the base model [14]. In Fig. (3), two compartments can be observed: an almost cubic, and an elongated one. The almost cubic compartment is based on the geometry of the experiments by [13]. The second compartment has the same dimensions except for the depth, which is doubled compared to the former.



(a) (b)

Fig. 3. (a) Sketch of the geometries used for the cubic compartment (left) and large compartment (right). The grey areas at the front schematically indicate the openings that allow for variation. (b) FDS visualization of the model using Smokeview (SMV).

A difference between the simulated and experimental models is that the former varies its opening at a constant height (doors open and close horizontally), while the latter varies its opening at a constant width (with vertical movements). Despite this modification in the opening, the validation of the temperatures were not affected.

Table 2 summarizes some of the simulation parameters.

Table 2. Simulation Parameters and values.

Simulation Parameter	Values
Cell size (m)	0.02 x 0.02 x 0.02
Time (s)	750
Fuel	Propane
Heat of Combustion (kJ/g)	46.45
Combustion Efficiency	0.9
Soot Yield	0.01

Propane (C_3H_8) was used as fuel, and the combustion model used in FDS assumes that the reaction is mixing-controlled with a single-step instantaneous reaction chemistry [10, 15].

Due to the size of the holes and the mesh resolution, the effective area was maintained, but 16 square burners were employed instead as an equivalent setup. A total of 26 and 42 meshes were used for the cubic and elongated compartments, respectively, in order to maintain the resolution. In the burner area, cubic cells with a side length of 1 cm were used, while in the area away from the fire, 2 cm cells were used. The criterion for the mesh selection was based on the size of the burners and the computational cost. Since these are 2x2 cm^2 it was ensured that each burner had at least four cells on the combustion surface.

RESULTS & DISCUSSION

Thermocouples Tree Layers & Temperature field

CFD models are validated through comparison with experimental data. In this particular case, the simulations were compared for all cases, focusing specifically on the temperature field, as a proxy of the velocity field.

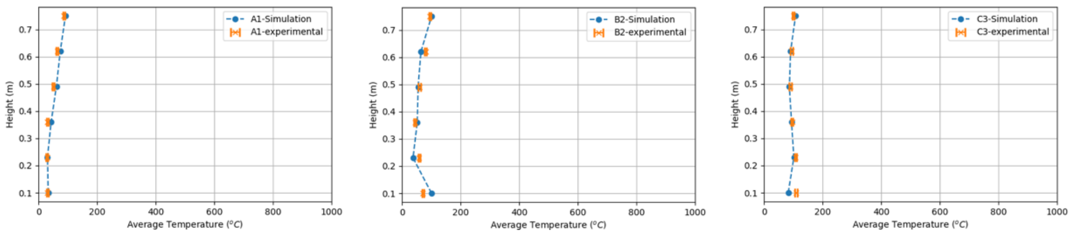
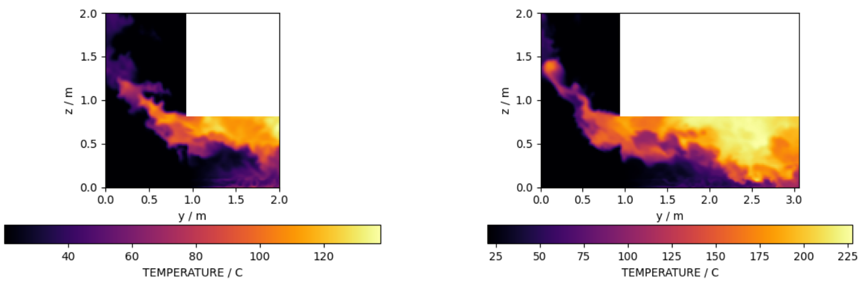


Fig. 4. Simulated vs experimental temperatures for three thermocouple trees distributed within the compartment at steady-state.

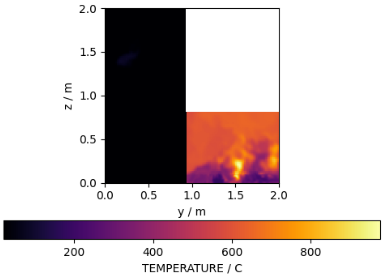
In Fig. 4, comparisons between simulated and experimental data for three thermocouple trees distributed within the compartment are presented (A1, B2 and C3 are the location of the thermocouples trees). As can be observed, the thermocouple measurement error is on the order of 4% [14], and the simulated temperatures show good agreement with their experimental counterparts in both values and trends.

This validation confirms that, for this scenario, the temperature field can be inferred. One of the simplifying assumptions enabling this analysis is that the fluid is thermally-driven by buoyancy, following the Boussinesq approximation. This approach, implemented in FDS [8], directly relates density to temperature [16]. From these experiments and the resulting temperature distribution, it can be observed that the compartment behaves as a well-stirred reactor when in *Regime I* [17].

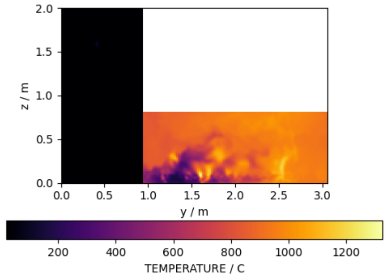
In Fig. 5, temperature slices in the steady-state are shown using Smokeview. As can be observed in both compartment cases, the opening is at 100%, falling in a *Regime II* compartment behaviour. Consistent with the qualitative definition provided by Thomas et al. [17], in a fuel-controlled post-flashover fire, there is no unified temperature distribution; rather, a temperature gradient exists as well as vertical velocities within the compartment.



(a) (b)



(c)



(d)

Fig. 5. Slice of temperature visualization through Smokeview (a) Quasi-cubic compartment with 100% opening, (b) Elongated compartment with 100% opening, (c) Quasi -cubic compartment with 20% opening and (d) Elongated compartment with 20% opening.

It is noticeable that the gas temperatures (in Fig. 5 (a) and (b)) are relatively low, with the maximum observed temperature being approximately 225ºC. This due to the high rate of hot gases exiting the compartment increasing the energy losses through the opening. It is worth noting that, in this particular case, the outgoing flow corresponds to smoke rather than external flaming. Nevertheless, depending on the compartment size and shape, external flaming could also occur in *Regime II* compartment fires.

It is also noticeable that – under the *Regime II* of behaviour – the maximum gas temperature in the elongated compartment is higher than the maximum gas temperature in the quasi-cubic compartment. This is not trivial, given that the same effective burner area and the same HRR are used, meaning the power of the fire is identical as well as the opening factor. The fact the temperature is higher in the elongated configuration is due to the residence time inside the compartment. It is worth noting that if the compartment fire fell under a *Regime I* behaviour, then, as per the theoretical assessment by [15], which includes several *classic compartment fire framework* assumptions, the maximum gas temperature would be higher in the quasi-cubic compartment given that it ends up being a direct function of the opening factor provided the same conditions are met (HRR, ambient temperature, and thermal conduction heat transfer coefficient).

Flow Field

This subsection presents the streamlines of the inflow and outflow within the compartment. In Fig. 6, the streamlines for the quasi-cubic and elongated compartments are shown, with 100% opening and three fire power levels.

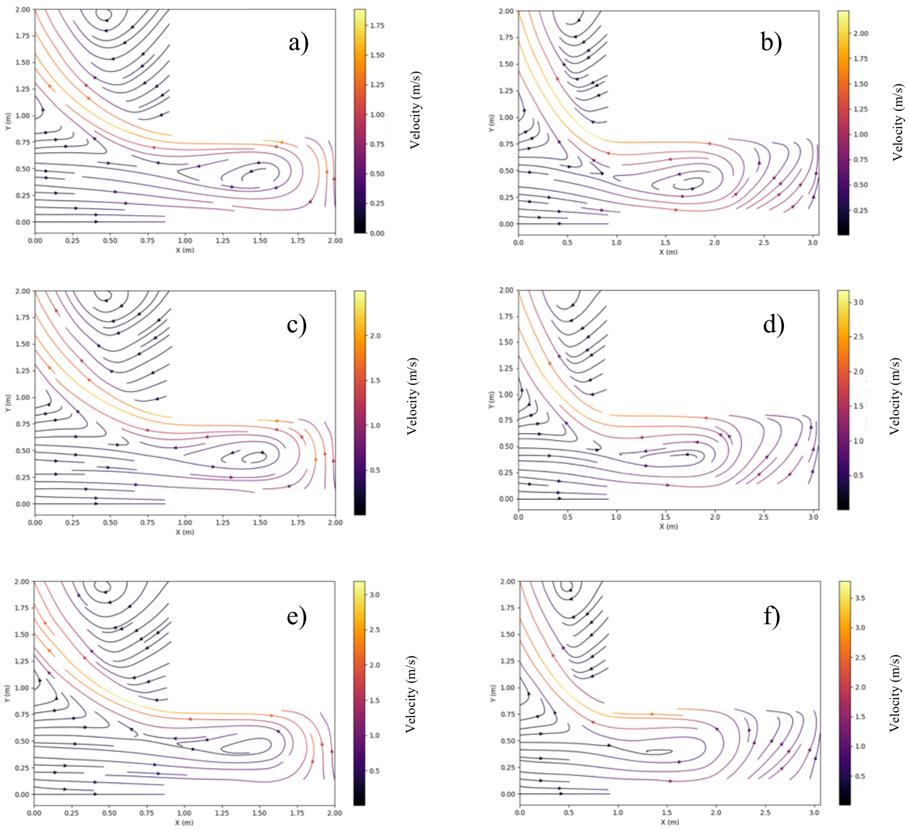


Fig. 6. Streamlines of the flow field. a) Quasi-cubic compartment and small fire, c) Quasi-cubic compartment and medium fire, e) Quasi-cubic compartment and large fire, b) Elongated compartment and small fire, d) Elongated compartment and medium fire, f) Elongated compartment and large fire.

In Fig. 6, at first glance, there do not appear to be significant differences between the quasi-cubic and elongated compartments. However, the first noticeable observation is that the outflow of hot gases and smoke increases its velocity (local-instant maximum) in the elongated compartment by 14%, 50% and 16%, respectively. This increase in outflow velocity becomes even more significant when analysing the increase in fire power for both compartments.

Regarding the incoming flow, in the quasi-cubic compartment it follows a horizontal trajectory, colliding with the rear wall and changing direction, eventually heading to the outside. In contrast, for the elongated compartment, the inflow enters in a slower motion, with the fire-induced buoyancy force diverting the flow upwards. This force, combined with the inflow's inertial force, diverts the incoming flow toward the figure's upper right corner (i.e. towards the back wall and upwards in a symmetrical fashion).

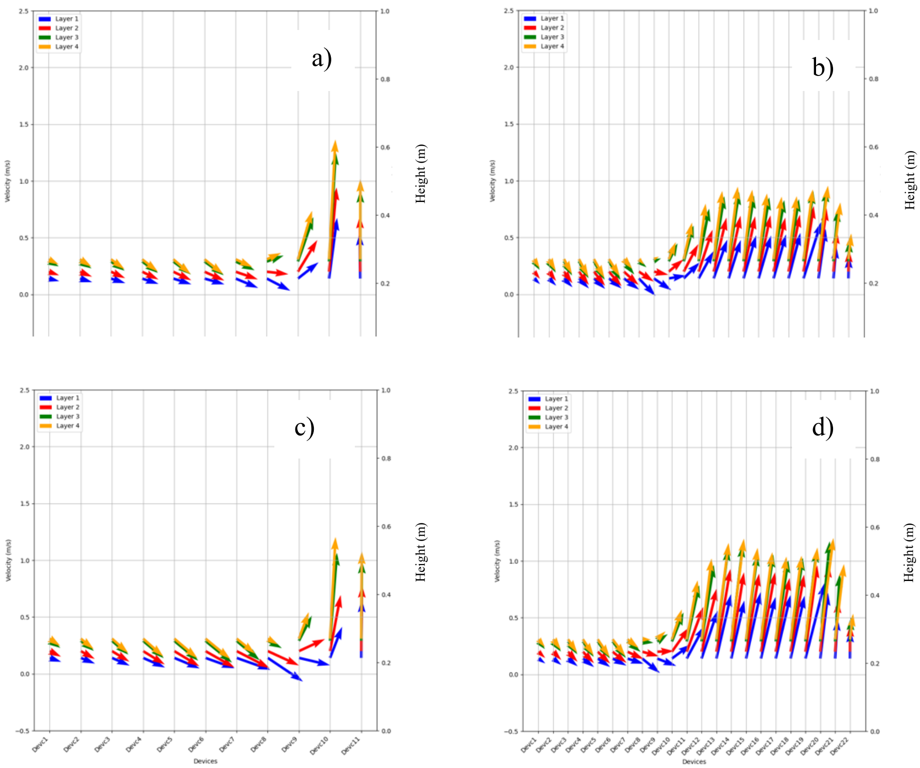
The most important distinction is that in the elongated compartment, the flame's buoyancy effect significantly influence the fluid dynamics, pushing the flow towards the top-back edge of the compartment. This fluid deflection in that directions is also attributed to the flame tilting caused by the incoming flow itself [19]. This fluid dynamics effect is not accounted for the classical regime definitions provided by Thomas [3].

Inflow devices

The main results of the simulations conducted are presented. Streamlines flow graphs were created for all cases. For the sake of brevity, only the most extreme cases are shown. Figure 7 presents the air inflow vector flows for each scenario.

Figures 7 a), c) and e) show the quasi-cubic compartment with a small, medium and large fire, respectively. It is evident that as the fire intensity increases, the vectors closer to the opening increase in magnitude, deviating more quickly towards the base of the fire source evidencing a fire-induced inflow (ventilation mode). Further, it can be observed that the velocity rapidly deviates upwards towards the ceiling. This sudden change is not clearly distinguishable as being due to the buoyancy force of the fire plume or due to the *backwall effect* [14], or both. Moreover, it can also be seen that the incoming flow enters horizontally, and due to its strong momentum, it pushes the flames towards the back of the compartment. This phenomenon is also evident in the temperature field shown in Fig.5.

Figures 7 b), d) and f) present the elongated compartment with a small, a medium and a large fire, respectively. It can be observed that, in this case, as the fire intensity increases, the vectors closer to the opening do not increase in magnitude evidencing a compartment-induced inflow (ventilation mode). Similar to the previous case, the buoyancy force of the fire plume increases as the fire power increases, evidenced by the vectors being sharply directed towards the ceiling.



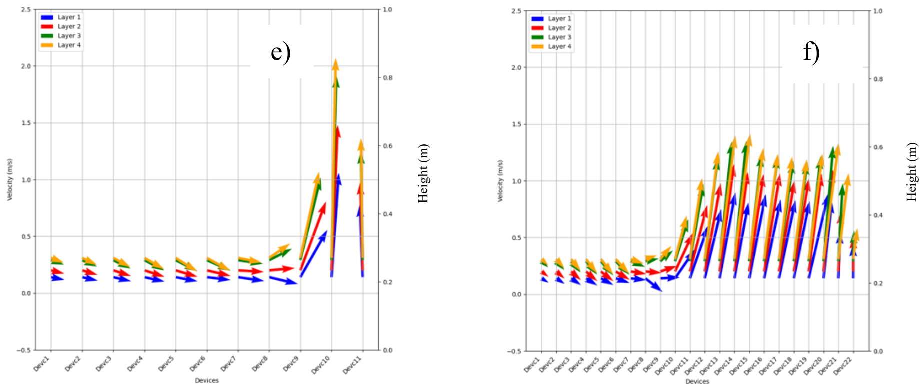


Fig. 7. Velocity decomposition of the inflow for the100% opening configuration. a) Quasi-cubic compartment and small fire, c) Quasi-cubic compartment and medium fire, e) Quasi-cubic compartment and large fire, b) Elongated compartment and small fire, d) Elongated compartment and medium fire, f) Elongated compartment and large fire.

Comparing the penultimate DEVC from the flow field graphs, DEVC10 for the quasi-cubic compartment, and DEVC21 for the elongated compartment, an increase in the vertical velocity of approximately 35% is observed in the quasi-cubic vs the elongated case. As mentioned above [14], this is due to the backwall effect.

CONCLUSION

Fully-developed fires have been historically studied within the classic compartment fire framework to understand the implications of a fire on the fire compartment's boundaries for purposes such as structural performance – namely fire resistance – and compartmentation through boundary integrity as a means to contain the fire in, and halting its spread from, the room of origin. This framework's most significant characterisation and contribution is the compartment's regime of behaviour, described by the relationship between the ventilation and the burning rate which, at the time, defined 2 clear regimes – Regime I and Regime II – with a somewhat clear break-point numerically determined by the ratio of direct surrogates to the ventilation and to the burning rate: opening size and amount of fuel, respectively.

The classic compartment fire framework emerged from testing small and near-cubic compartments with a single and vertical opening. It is a robust representation of these type of compartments and within its bounds of applicability – i.e. acknowledging and validating its underlying assumptions – there is no fundamental weakness with it. Nevertheless, its characterisation is intimately linked to the geometry of the compartment, as well known by the founding authors [3,4] but forgotten along the last four decades.

Contemporary architecture challenges the framework's underlying assumptions, particularly those related to the compartment geometry, and several relevant intermediate behaviours have been described [13] as a consequence of modifying this variable. This study analyses the impact of geometry on the development of temperature and flow fields in a compartment fire under well-ventilated conditions using computational models which's results, once more, exhibit intermediate or modified regimes of behaviour.

In regards to the temperature field, it was found that under the same HRR, opening factor and thermal conductivity coefficient, the maximum gas temperature in the elongated compartment was higher than the maximum gas temperature in the quasi-cubic compartment due, in principle, to a longer residence time inside the compartment. Although comparing two compartments under arguably Regime II behaviours, this finding challenges one of the classic compartment fire framework misinterpreted certainties that Regime II fires have lower temperatures than Regime I fires by default, precisely due to factoring out a crucial variable: the compartment's geometry.

In regards, to the flow field, the most relevant finding is that not only the flame's buoyancy but also the compartment's geometry (in this case it's depth) significantly influences the fluid dynamics. In the elongated compartment, a more natural (i.e. less influenced by the compartment) flow pattern is observed, with a slower inflow of fresh air, and a faster outflow of hot gases, compared to the shorter compartment. Contrary, in the latter, and of notable significance, is the effect that the back wall has on the magnitude and direction of the flow velocity: it was found that the vertical component of the velocity increased by approximately 35% and thus the flow pattern was altered due to this effect.

None of these fluid dynamics effects are accounted for in the classic regime definitions provided by Thomas [3], given its focus on semi-cubic and small compartments with a single and vertical opening. This configuration is not representative of real fires in contemporary architecture.

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