Experimental investigation of the "Ventilated Façade" system performance under fire conditions

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ABSTRACT

The ventilated façade (VF) system is a double-wall construction, comprising an external lightweight cladding panel and the building's façade, which is used to increase the indoor comfort level (e.g. temperature, humidity) in buildings. Literature reports on VF systems focus mainly on investigating their behavior in terms of energy consumption reduction; there are only scarce reports on the fire behavior of such systems. However, during a fire event, VF systems may contribute to fire spreading on the facade, representing a significant risk to the upper floors of a building, especially in the case of externally venting flames. Aiming to investigate the fire behavior of the VF concept a large scale compartment fire test was carried out. An extensive set of sensors is installed both inside and outside the test compartment, aiming to record the temporal variation of several important physical parameters (gas and wall surface temperatures, gas velocities, mass loss rate). Particular emphasis has been given on the estimation of the thermal characteristics of the fire compartment and subsequent EVF, as these are the main physical parameters affecting the heat exposure of the VF façade system. Experimental results suggest that the VF system proved to sufficiently sustain the 900 s fire exposure.

Keywords: Ventilated façade, fire behavior, externally venting flames, heat exposure

1. INTRODUCTION

Primary energy use in buildings accounts for approximately 40% of the total annual energy consumption and CO_2 emissions in the European Union. There is a large variety of construction techniques and materials available that can be used to improve the energy efficiency of buildings. Aiming to significantly reduce the total building energy demand, a range of systems that make use of renewable energy sources, such as solar energy, have been developed. One such system is the opaque ventilated façade (or rainscreen) concept, which is used to take advantage of the incident solar radiation on the building's façade. The ventilated façade (VF) system is essentially a double-wall construction, comprising an external lightweight cladding panel and the building's façade (outdoor side of the external wall); these two layers are separated by an air cavity. The external cladding panel is heated by the incident solar radiation, thus heating the air in the cavity; the heated air flows upwards, due to thermal buoyancy (natural convection). Ambient air is allowed to enter and exit the cavity through ventilation openings in its lower and upper side. The upwards air flow developing in the air cavity provides a range of advantages in terms of energy consumption for heating and cooling, as well as prevention of moisture penetration. VF systems may be installed both in new and existing buildings (energy refurbishment).

VF systems were initially designed in order to protect buildings against rain and wind, enhancing wall durability and, eventually, improving energy performance. The system's energy performance is owed to the existence of the air cavity between the building's wall and the external cladding. Due to the incident solar radiation, the external cladding panel is heated, thus heating the air in the cavity; the heated air flows upwards, due to thermal buoyancy (natural convection), Figure 1 (left). Ambient air is allowed to enter and exit the cavity through ventilation openings in its lower and upper side. The air movement through this air cavity, due to the "chimney effect", contributes to limiting the appearance of moisture from rain or condensation. In the case of hot weather conditions, the amount of heat absorbed by the building can be reduced due to the partial reflection of solar radiation by the external coating and the air gap. As a result, ventilated façade systems are earning increasing recognition in contemporary architecture since they may be installed both in new and existing buildings (energy refurbishment).

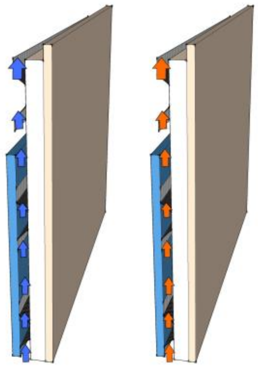


Figure 1 Ventilated façade system; "chimney effect" (left) and flames and hot gases pathway during a fire event (right).

Literature reports on VF systems focus mainly on investigating their behaviour in terms of energy consumption reduction; there are only scarce reports on the fire behaviour of such systems. However, during a fire event, VF systems may contribute to fire spreading on the facade, representing a significant risk to the upper floors of a building, especially in the case of externally venting flames (EVF). The "chimney effect" in such a case poses a severe threat, as the air cavity may serve as a pathway for the fire to spread beyond the room of fire origin, Figure 1 (right). Although several authors have highlighted the effect of the façade geometric characteristics on EVF development and propagation (Yokoi, 1960; Oleszkiewicz, 1989) there are scarce reports focusing on façade ventilated cavities, such as double skin facades (Chow, 2003; Chow and Hung, 2006; Chow, 2014), and more particularly or VF systems (Jeffs et al., 1986; Giraldo et al., 2013).

Once the fire enters the air cavity, the hazards associated with fire spreading depend on the following factors (Giraldo et al. 2013):

- **Thermal properties of insulation:** The fire intensity increases when combustible insulation materials are used.
- **Structure of the façade:** The temperature within the fire envelope may achieve a local temperature exceeding 600^{o}C. Regardless of the external panel construction, if the fire enters the cavity and comes into contact with the metal substructure, the latter may lose its strength and integrity as it is heated; under prolonged fire exposure conditions, the railing system could melt and may lead to localized system collapse.
- **Cavity shape and "chimney effect":** The fire spread in a VF system occurs through the windows and the air cavity. This may occur simultaneously. When flames are

confined by the cavity, they may become elongated as they seek oxygen and fuel to support the combustion process. This phenomenon, closely associated with the "chimney effect", may lead to flame extension up to ten times greater than that of the fire plume spreading through the windows, regardless of the materials used as insulation. This may enable fire to spread quickly and unseen through the external cladding system, if appropriate fire barriers have not been provided.

- **Vulnerable areas:** The window and door frames may provide a direct entry route to the air cavity. These are usually made of aluminum or PVC and lack fire barriers or seals.

Preventing fire spread in the air cavity is crucial. The use of fire stops may prevent fire spread through the air cavity but currently there is a lack of test standards to support selection of appropriate fire stops. In this context, the main scope of this work is to investigate the underlying phenomena affecting fire behaviour characteristics of the VF system, by means of a large-scale compartment-façade fire test.

2. LARGE SCALE EXPERIMENTAL SETUP

Aiming to investigate the fire behaviour of the VF concept a large-scale natural fire test was performed at the premises of Greek Firefighting Academy (Figure 2). Figure 3 presents a schematic drawing of the large scale compartment-façade experimental apparatus. The timber frame compartment was lined with two layers of 12.5 mm fire resistant gypsum plasterboards. The internal dimensions of the test compartment measured 1760 mm x 800 mm x 2100 mm. The compartment exhibits a single opening (window), measuring 765 mm x 1100 mm.

Figure 2. Indicative photos of the fire test configuration and the experimental setup.

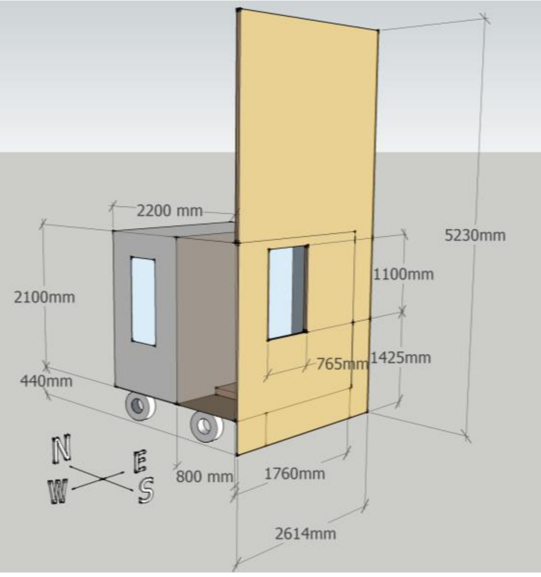


Figure 3 Schematic drawing of the large scale compartment-VF configuration.

The external façade wall measured 2614 mm x 5230 mm. The window is located on the S side; the distance of the window sill from the compartment's floor is 940 mm. The façade surface is formed using commercial 15 mm thick gypsum plasterboard; timber studs and battens are used to support the façade on top of the compartment, Figure 4. The external cladding panels, comprising 12.5 mm thick cement boards covered by a 5 mm thick layer of plaster coating, are supported using perforated steel studs, at distances as indicated in Figure 5; the width of the air cavity formed between the two layers is 25 mm. An opening on the upper side of the widow frame (lintel) supplies ambient air to the air cavity, following the construction practice used in commercial solutions; the other 3 sides of the window frame are closed.

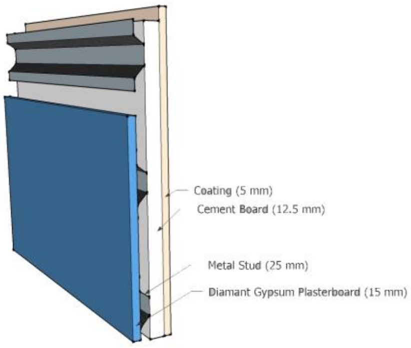


Figure 4 Schematic drawing of the VF wall assembly configuration.

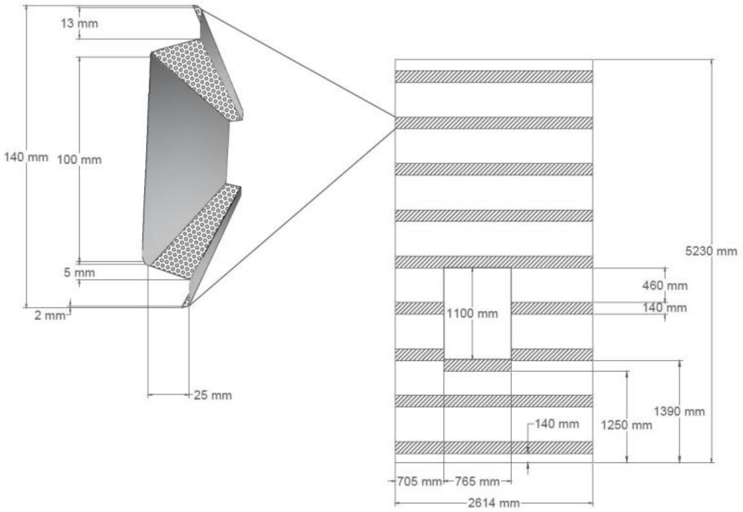


Figure 5 Schematic drawing of the steel stud geometry (left) and the stud locations on the exposed face of the gypsum plasterboard (right).

3. SENSORS AND DATA ACQUISITION SYSTEM

An extensive set of sensors was installed both inside and outside the test compartment, aiming to record the temporal variation of several important physical parameters (gas and wall surface temperatures, gas velocities, mass loss rate). Emphasis was given to the characterization of the temperature environment adjacent to the façade wall along the height of the EVF plume. Towards this end, 30 K-type thermocouples, 1.5 mm in diameter were used to measure gas temperatures in the vicinity of the flame, whereas 34 additional K-type thermocouples were installed at various heights along the façade, aiming to record wall surface temperatures at the exposed and unexposed sides of the VF system panels, as well as the thermal field developing inside the air cavity. Figure 6 depicts the positioning of the thermocouples at each different layer along the VF system. Positions “1” and “2” correspond to the unexposed and exposed surface of the internal gypsum plasterboard. Position “3” records temperatures at the middle of the air cavity and finally positions “4” and “5” correspond to the unexposed and exposed surface of the external board, consisting of the cement board and the plaster coating.

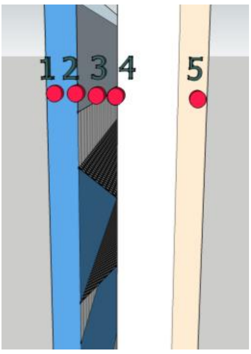


Figure 6 Positioning of the thermocouples at each different layer along the VF system.

Although emphasis was given on Externally Venting Flames (EVF) characteristics, the importance of the compartment thermal conditions was also investigated. Towards this end, 5 K-type thermocouples, located at different heights at the geometrical centre of the compartment and 4 thermocouples vertically distributed at the centreline of the opening, were used to monitor the temperature profiles developing at the interior of the fire compartment, Figure 7. The recorded thermocouple data, obtained at the interior of the compartment, were corrected for radiation using a “post-processing” methodology (Kolaitis et al., 2014). All thermocouples measurements were recorded using a Universal Data Logging Interface designed in LabView software; the sampling frequency was 1 s.

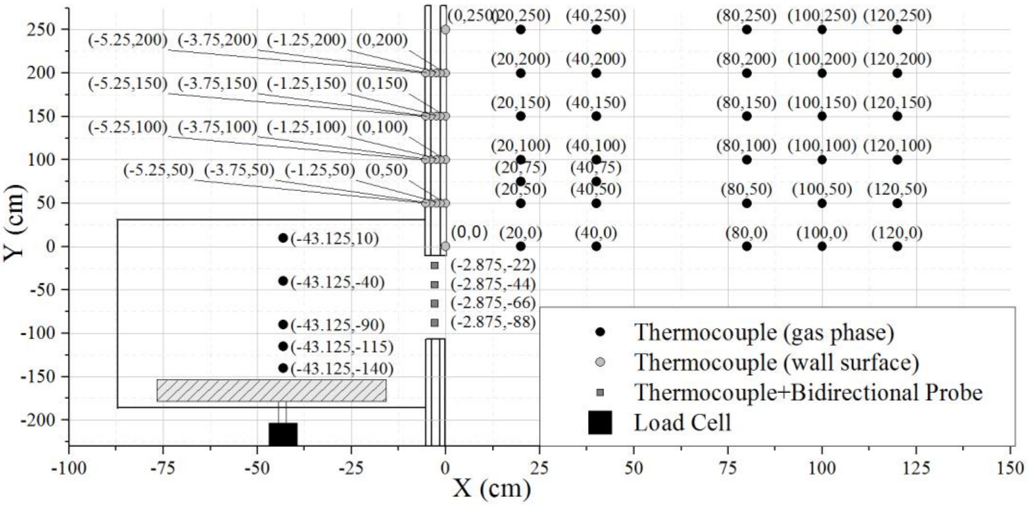


Figure 7 Schematic of the large-scale compartment façade configuration, depicting locations of measurement equipment.

In addition, measurements of velocity of gases entering and exiting the fire compartment through the window were acquired with a vertical array of four bidirectional probes placed on the centreline of the window, supplemented by thermocouples located at the same positions, as shown in Figure 7. This arrangement allowed the velocity results measured with the bi-directional probes to be temperature compensated. Bidirectional probes measure the flow velocity of a fluid using a pressure differential. This device possesses two features ideally suited for application in fire research, in addition to being as rugged as a stainless steel pitot-static tube: angular insensitivity (measurements are accurate at a maximum angle of 50 degrees between the tube and the air flow), which allows a more accurate assessment of velocity where flow angles are difficult to predict; and secondary, owing to its symmetric nature, the probe responds to flow in either direction. This bidirectional property allows the probes to be located without prior knowledge of flow direction. The probe responds correctly when the flow at a point reverses its direction, e.g. when the opening neutral plane is lowered as a room fills during the build-up of a fire or when transient recirculation is occurring. The probe consisted of a section of circular stainless steel tube of a 22 mm diameter with a barrier midway between the end points, which divided the tube into two chambers. The upstream chamber senses the pressure closer to the stagnation pressure of the flow. The downstream chamber senses a pressure slightly below the static pressure of the flow. The pressure sensing lines were tapped with silica hoses and led to an Omega PX277-0.1D5V differential pressure transducer which in turn was connected to the data logger. Conversion of the raw bi-directional velocity probe has been performed according to the work of McCaffrey and Heskestad on the design and calibration of bidirectional low-velocity probes for flame and fire applications (McCaffrey and Heskestad, 1976).

A stainless steel rectangular pan, measuring 700 mm x 700 mm x 250 mm, was installed at the geometrical centre of the room, 100 mm above the compartment floor in order to hold the 56.7 kg of liquid fuel; n-hexane was used as the liquid fuel of choice. The lower heating value of the n-hexane used in the tests was estimated, using an isoperibolic oxygen bomb calorimeter (ASTM D240-14), to be 43521.17 kJ/kg. The fuel mass was continuously monitored using a load cell, exhibiting a 2 mV/V sensitivity at a capacity of 500 kg, installed under the pan. This "expendable" fuel source was employed to better simulate realistic building fire conditions. The fire load and opening dimensions were selected in order to establish strongly under-ventilated fire conditions, thus ensuring the development of an EVF (Figure 1). The peak fire power achieved, estimated using the instantaneous mass loss rate, was 3 MW.

Variations in flame shape and position are recorded using 2 video cameras positioned opposite the facade, at a distance of 8.60 m, and at a right angle to the opening, at a distance of 9.40 m, at 30 frames per second. The obtained measurements provide a detailed physical description of the main characteristics of the turbulent, reactive and multi-component flow-field developing inside and outside the test compartment, as well as at the various layers of the VF system. A thermal camera was positioned 8.60 m away from the apparatus facing the façade to record additional information regarding the thermal response of the façade surface.

4. RESULTS

4.1. Fuel Consumption Rate

Mass loss rate (MLR) is an important parameter in the evaluation of fire hazards. The combustion rate of a pool fire in a compartment is influenced by a variety of parameters such as ventilation, radiation from the surrounding walls and thermal characteristics of the exposed rim above the fuel (Thomas et al., 2007; DiNenno et al., 2002). An almost constant fuel combustion rate can be observed throughout the experiment duration, Figure 8. The pool fire is observed to burn steadily until it enters the decay stage after approximately 850 s. The rather noisy signal is attributed to the increased turbulence at the interior of the compartment.

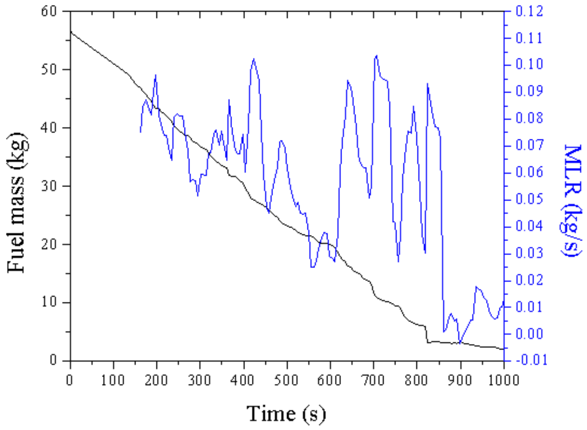


Figure 8 Measurements of fuel mass and instantaneous fuel mass consumption rate

4.2. Compartment Gas Temperatures

Gas temperature evolution inside the compartment is depicted in Figure 9. The three characteristic stages of fire growth, quasi steady state (corresponding to fully developed fire conditions) and decay phase, typically encountered in compartment fires, can be easily identified. As shown in Figure 9, temperatures at all heights increase rapidly after ignition and only the temperature at the lowest position just above the fuel pan decreases to a low temperature, at approximately 600^{o}C, during the quasi-steady case. This is because the particular thermocouple was quickly heated up by the flame after ignition but temperature decreased as the flames inclined towards the window. Generally, during fully developed fire conditions the gas temperature at the interior of the compartment fluctuates at a steady value while remaining practically constant. As expected, gas temperature values increase with increasing height; maximum values in the interior of the compartment reached 1100^{o}C.

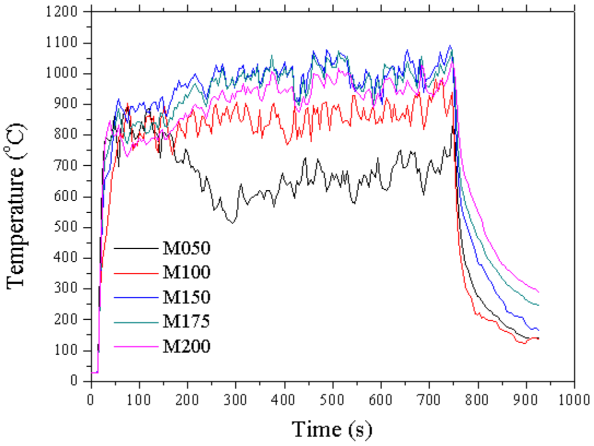


Figure 9 Temperature measurements at the interior of the compartment at various heights.

4.3. *Opening Flow Velocities*

Velocity measurements at the centerline of the window at positions 22 cm, 44 cm, 66 cm and 88 cm below the window lintel are depicted in Figure 7. Negative velocities imply flow into the fire compartment. Incoming fresh air enters the compartment at an almost constant mass flow rate through the lower part of the opening, whereas hot, vitiated gases, unburnt volatiles and smoke exit through the upper part of the opening. The exit velocity of the hot vitiated gases, ranging from 2-4 m/s, is affected by the considerable swirling behavior of the EVF, owed to external environmental conditions and local air entrainment. It was visually observed that the overall effect of external wind resulted in tilting EVF towards the façade. The velocity of fresh air entering the fire compartment was considerably lower at approximately 1-2 m/s.

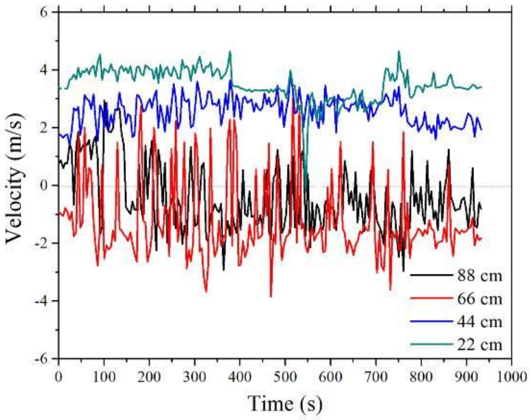


Figure 10 Velocity histories at the centreline of the opening at indicated heights below the window lintel.

4.4. *Flame Shape and Dimensions*

A representative EVF time line during the experiment is depicted in Figures 11 and 12 respectively at successive times; stages of internal combustion and continuous EVF can be observed. During the initial stages of fire development, where there is enough oxygen in the compartment, combustion is limited in the interior. As soon as the oxygen is depleted, flames stretch in the horizontal direction, gradually spreading over the ceiling. At approximately 120 s after fire initiation, EVF start emerging from the opening due to the expansion of the buoyant turbulent flame at the interior of the compartment. Throughout this latter stage, an oscillating behaviour of EVF is observed and EVF volume is highly fluctuating depending on external wind direction.

Flames are projected from the fire compartment approximately at an angle of 45° to the horizontal through the upper half of the opening and bend upwards, Figure 12. At specific instances, the EVF tend to curl back, due to peripheral air entrainment and impinge upon the wall above the opening. The EVF itshelf acts as a radiation source and as it evolves towards the surface of the façade it imposes a convective heat flux. The façade absorbs heat from the plume and the exposed surface temperature may reach up to 500°C (Figure 13).

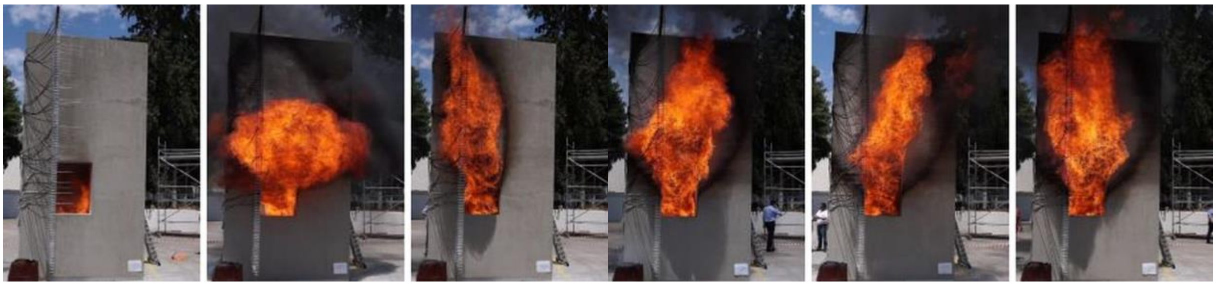


Figure 11 EVF development at 2.5 min intervals (front view).

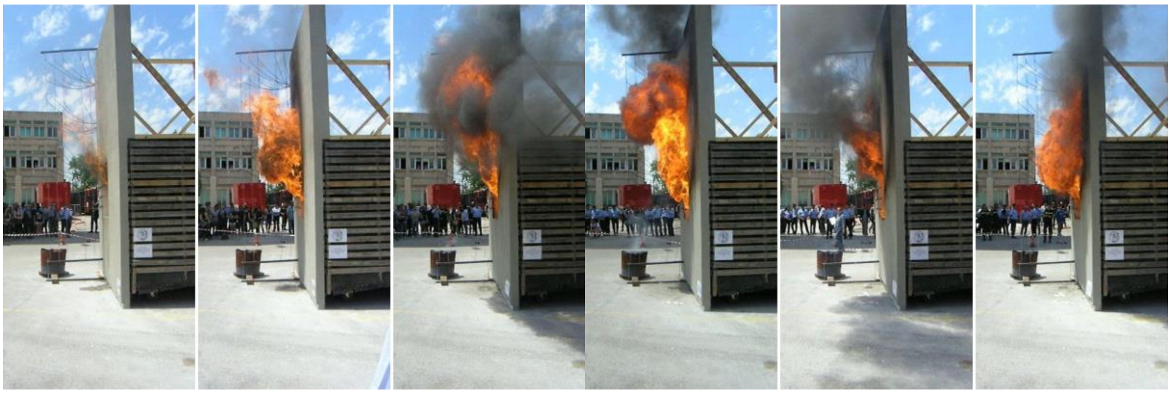


Figure 12 EVF development at 2.5 min intervals (side view).

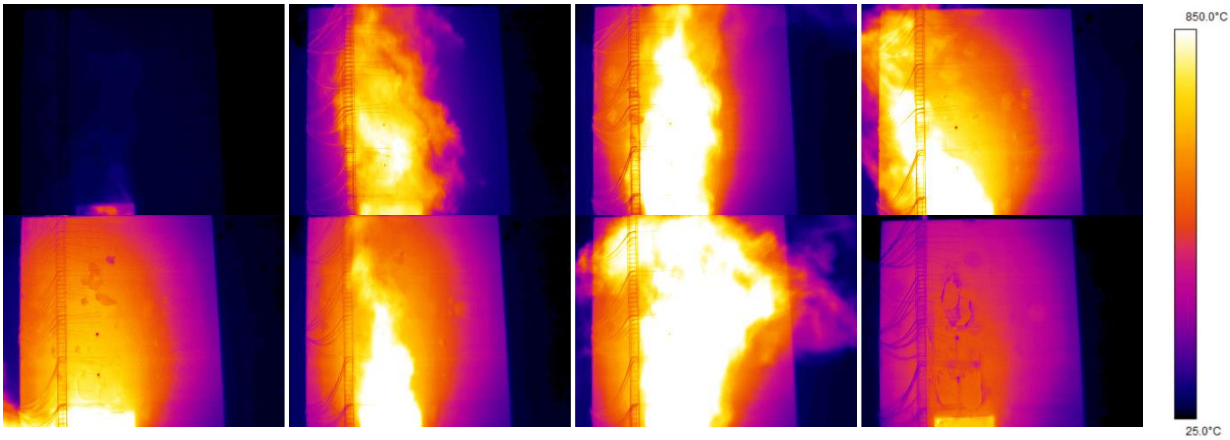


Figure 13 Thermal camera images of the front side of the façade at 2.5 min intervals.

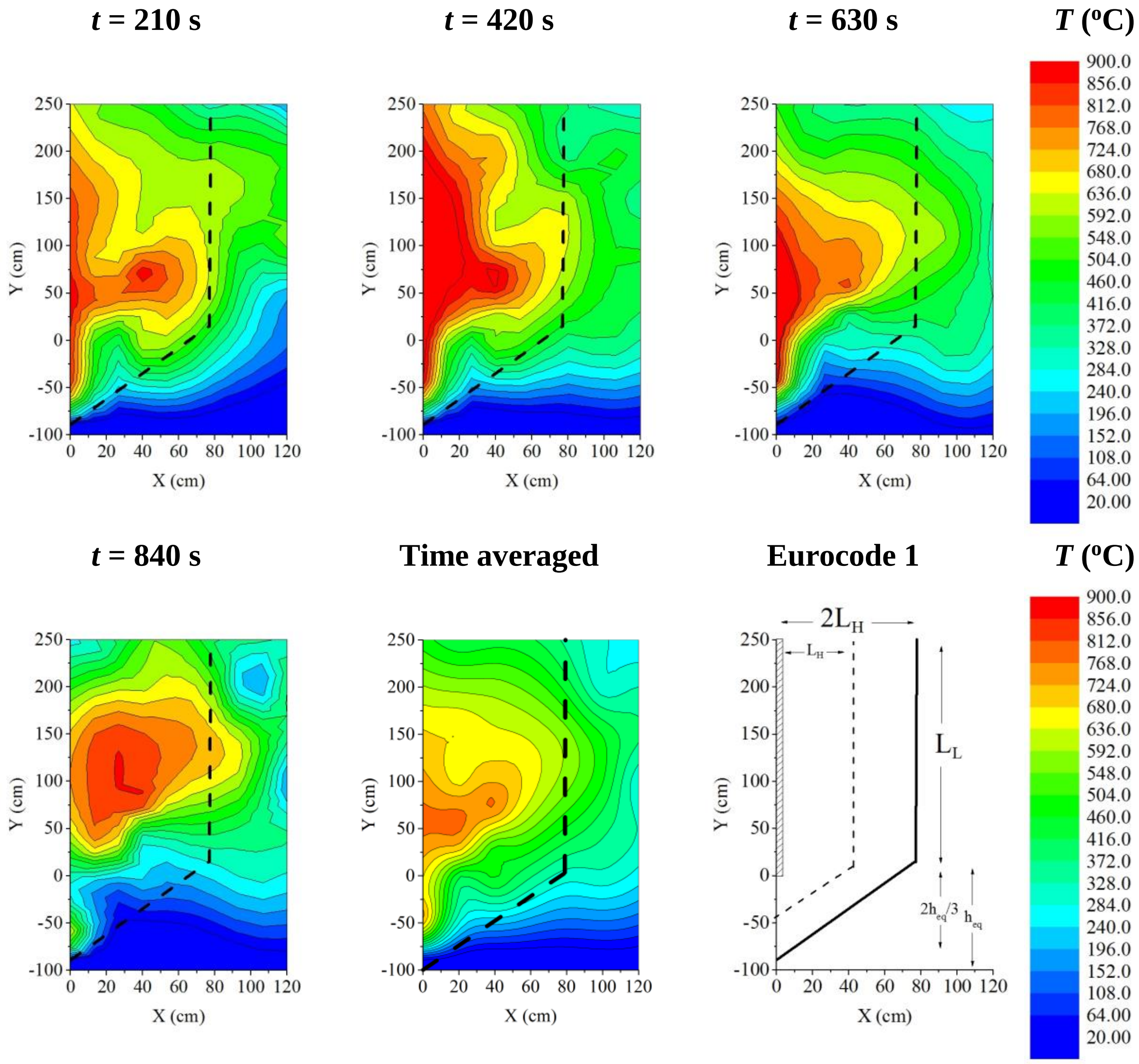
4.5. Centreline Temperature

Temperature contour plots shown in Figure 14 assist in determining the spatial distribution of the EVF-induced thermal field developing outside the compartment. The depicted data were obtained by linear interpolation of the temperature measurements obtained at the exterior of the fire compartment. Four characteristic instances have been chosen, namely at 210 s, 420 s, 630 s and 840 s, in order to assess EVF characteristics throughout the duration of the fire event. Supplementary, in order to acquire an overall characterization of the EVF, time averaged data, throughout the entire duration of the fire test, are also depicted.

Calculated EVF dimensions according to Eurocode 1 (EN 1991-1-2, 2002) are depicted in the form of dashed black lines. Peak temperature values, up to 900^{o}C, are observed at the vicinity of the opening. EVF temperatures gradually decrease with increasing height. EVF dimensions calculated using the Eurocode 1 methodology slightly underestimate EVF projection as depicted in the time averaged temperature contour plot.

4.6. Façade Temperature

Temporal evolution of the temperature measurement at the VF system faces is depicted in Figure 15 at the measurement positions indicated in Figure 6. On the unexposed face of the VF system (position 1) temperatures increased slowly during the first 200 s and remained constant throughout the duration of the test. According to the Australian Standard AS1530.4, a plasterboard wall fails when the maximum temperature rise (above the ambient temperature) of the ambient facing side (unexposed side) exceeds 180^{o}C (Clancy, 2002). Taking into account this criterion, it is safe to assume that the VF system proved to sufficiently sustain the 900 s fire exposure as in all measurement positions, the temperature of the unexposed face did not surpass 180^{o}C. Furthermore, gypsum plasterboards exposed to fire are considered to exhibit mechanical failure when cracks or openings are observed through the wall (Manzello et al., 2007); after the fire test conducted, no visual observation of cracks was made.


t = 210 s

t = 420 s

t = 630 s

t = 840 s

Time averaged

Eurocode 1

Figure 14 Temperature contours at the centreline plane perpendicular to the façade at various time instances and time-averaged throughout the duration of the experiment.

As depicted in the sudden increase in temperature measurements in the air gap (position 3) at 50 cm height, when EVF start to emerge from the opening the flame heats the top part of the opening. Subsequently, the exposed surface of the gypsum plasterboard (position 4) is instantly heated, but as EVF progressively evolve at the exterior of the compartment a considerable portion of the hot gases tend to exit from the upper part of the opening rather than through the air gap above the window lintel. Temperature values vary depending on the measurement position, becoming progressively higher as positions increase in height from 50 cm to 200 cm above the window lintel. From visual observation it was noted that flames did not pass through the air gap, only hot vitiated gases.

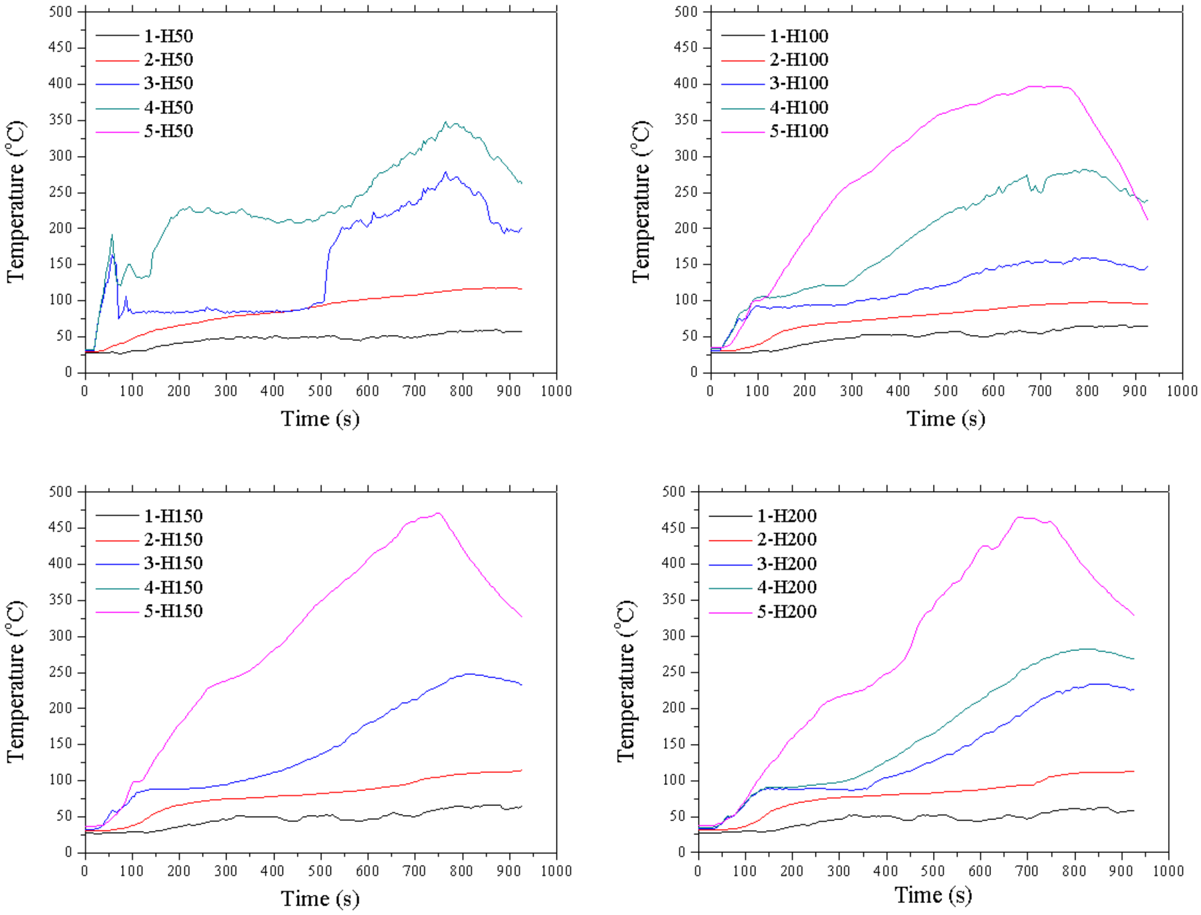


Figure 15 Temperature measurements at the various interfaces of the VF system (c.f. Figure 6), at a height of 50 cm (top left), 100 cm (top right), 150 cm (bottom left) and 200 cm (bottom right) above the window lintel.

5. CONCLUDING REMARKS

A large scale compartment façade fire test was carried out in order to assess the performance of VF systems under fire conditions. A particular emphasis has been given on the estimation of the thermal characteristics of the fire compartment and subsequent EVF, as these are the main physical parameters affecting the heat exposure of the VF façade system. More specifically, the fire spread behavior through the air gap was evaluated by means of temperature measurements at different heights. On the unexposed face of the VF system temperatures increased slowly and remained constant below 180°C throughout the whole fire experiment duration.

The obtained extensive set of experimental data, obtained in both the interior and the exterior of the fire compartment, can be used to address several aspects of EVF fire dynamics and its effect on VF systems under realistic fire loads. They can also be used to validate CFD models or evaluate the accuracy of fire engineering design correlations currently available.

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