A FULL-SCALE FIRE TEST TO INVESTIGATE THE FIRE BEHAVIOUR OF THE "VENTILATED FAÇADE" SYSTEM

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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 existing façade, which is used to increase indoor comfort levels (e.g. temperature, humidity) in buildings. 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 emerging externally venting flames. Aiming to investigate the fire behaviour of a typical VF system, a large scale compartment-facade fire test is 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, such as gas and wall surface temperatures, gas velocities and fuel mass loss rate. Emphasis is given on the estimation of the thermal characteristics of the externally venting flames, emerging close to the facade, since these are the main physical parameters affecting the heat exposure of the VF system. A commercial VF system is employed; no thermal insulation is used, aiming to investigate the main aerodynamic and thermal phenomena affecting the flow of hot gases and flames in the air cavity. In addition, no fire barriers are installed on the VF system, thus representing a "worst case" scenario for a VF system with no combustible materials. Analysis of the experimental data suggests that even though gaseous combustion products may manage to penetrate into the air cavity of the VF system, no consistent flaming conditions are established. In addition, wall surface temperatures on the unexposed side of the system remain constantly below 180°C throughout the duration of the fire test.

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 concepts that make use of renewable energy sources, such as solar energy, have been developed. One such system is the opaque ventilated façade (or rainscreen), which can be 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, formed using perforated steel studs. A thermal insulation layer is usually installed on one side of the 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 at its lower and upper sides. 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. For instance, in case of hot weather conditions, the amount of heat due to solar incident radiation penetrating into the building is reduced. In addition, VF systems offer additional protection against rain and wind, enhancing the façade wall durability. As a result, ventilated façade systems are increasingly used in new constructions, as well as in existing buildings (e.g. energy refurbishment).

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). In such a case, the "stack effect" may pose a severe threat, since the air cavity may serve as a pathway for the fire to spread above the level of the initial fire source. Although several authors have highlighted the effect of the façade geometric characteristics on EVF development and propagation [1,2] there are scarce reports focusing on ventilated façade cavities, such as double skin facades [3-5] or, the main subject of this work, VF systems [6,7].

Once flames enter the air cavity of the VF system, there are several factors that may affect the severity of the hazards associated with fire spreading [7]:

a) *Thermal insulation*: Aiming to increase the thermal performance of the VF system, a thermal insulation layer may be installed on one side of the air cavity. In case the thermal insulation material is combustible (e.g. polystyrene-based insulation), the fire spreading rate may be significantly increased.

b) *VF Structure*: When flames or hot gaseous combustion products enter the air cavity, they may come in contact with the substructure that is commonly used to separate the external cladding from the building's façade (perforated steel studs). Since the local temperature within the fire envelope may exceed 600ºC, the steel elements may lose their strength and integrity; under prolonged fire exposure conditions, the entire substructure system may fail, resulting in a partial or full system collapse.

c) *Air cavity shape and "stack effect"*: In case an EVF enters the air cavity, the severely under-ventilated conditions established inside the cavity, supported by the "stack effect", may lead to a substantial elongation of the flames; their total length may significantly exceed the length of the external fire plume. This may enable fire to spread quickly and unseen through the VF system, if appropriate fire barriers are not in place.

d) *Opening-cavity vulnerable areas*: Openings may provide the EVF and combustion products a direct entry route to the air cavity. Window and door frames are usually made of aluminium or PVC and lack fire barriers or seals.

It is evident that preventing fire spreading inside the air cavity is vital. The use of fire barriers may retard or event avert fire spreading through the air cavity, but currently there is a lack of explicit design guidelines or test standards to support selection of appropriate fire barriers. In this context, the main scope of this work is to investigate the main physical phenomena affecting the fire behaviour of the VF system, by means of a large-scale compartment-façade fire test.

2. LARGE-SCALE COMPARTMENT-FAÇADE FACILITY

Aiming to investigate the fire behaviour of the VF concept a large-scale natural fire test has been performed at the premises of the Greek Fire Academy (Figure 1, left). In order to generate an EVF, severely under-ventilated conditions were required. Towards this end, a small compartment was formed near the opening of an existing timber frame test compartment, by employing double-layer 12.5 mm fire resistant gypsum plasterboard walls. Figure 1 (right) presents a schematic drawing of the large scale compartment-façade experimental facility. The internal dimensions of the test compartment were 1760 mm x 800 mm x 2100 mm. The compartment exhibited a single opening (window) located on the S side, measuring 765 mm x 1100 mm; the distance of the window sill from the compartment's floor was 940 mm. The entire fire compartment was lined with a double-layer of 12.5 mm fire resistant gypsum plasterboards.

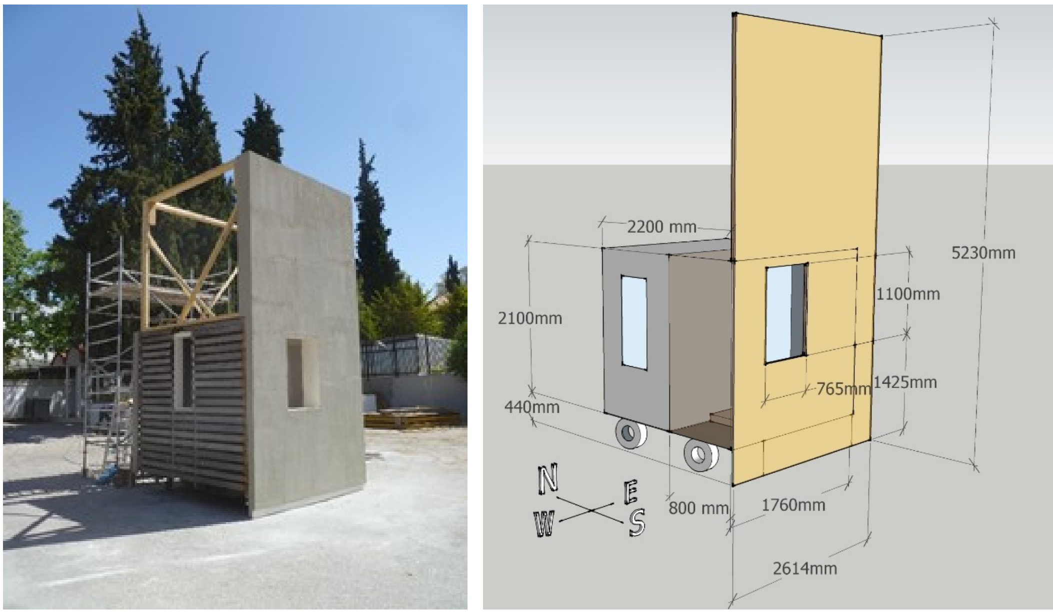

Figure 1. Indicative photograph (left) and schematic drawing (right) of the large-scale compartment-façade facility.

An external façade wall was attached to the fire compartment, using a commercial 15 mm thick gypsum plasterboard; timber studs and battens were used to support the façade on the top of the compartment (Figure 2, left). The external façade wall measured 2614 mm x 5230 mm. A commercial VF system was installed to the façade wall. The external cladding panels, comprising 12.5 mm thick cement boards covered externally by a 5 mm thick layer of plaster coating, were supported using perforated steel studs. The perforated studs were installed horizontally, in order to allow the upwards air movement in the cavity (Figure 2, middle). The width of the air cavity formed between the two layers was 25 mm. Following the construction practice employed in commercial VF solutions, an opening on the upper side of the widow frame (lintel) allowed ambient air to enter the air cavity (Figure 2, right); the other 3 sides of the window frame were closed.

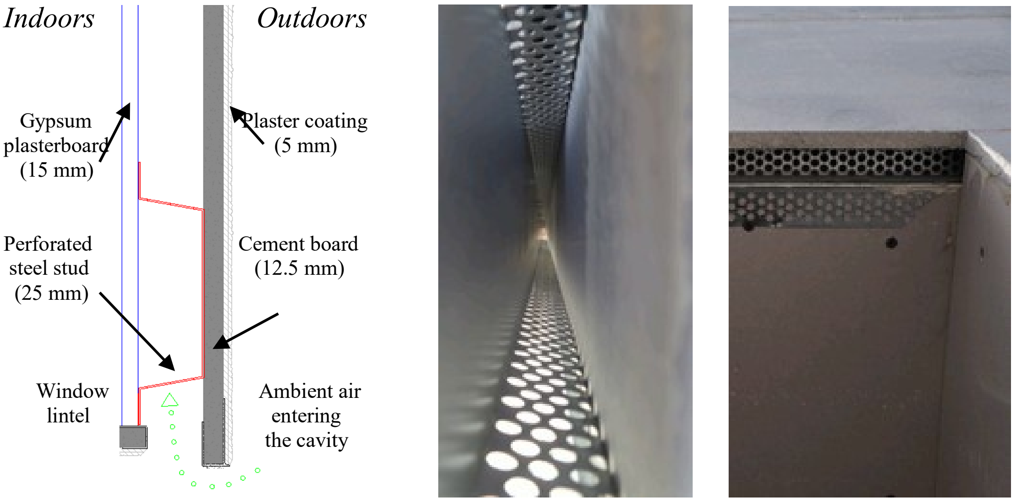

Figure 2. VF assembly schematic drawing (left), photograph of the perforated steel stud (middle) and detail of the (perforated) opening to the air cavity at the window lintel (right).

A stainless steel rectangular pan, measuring 700 mm x 700 mm x 250 mm, was installed at the geometrical centre of the test compartment, 100 mm above the compartment floor, in order to hold the 56.7 kg of n-hexane liquid fuel used as the fire load. The lower heating value of the n-hexane used in the tests was estimated, using an isoperibolic oxygen bomb calorimeter [8], to be 43521 kJ/kg. This "expendable" fuel source (natural fire) 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.

3. SENSORS AND DATA ACQUISITION SYSTEM

An extensive set of sensors (Figure 3) 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, fuel 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. In addition, 34 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. Although emphasis was given on Externally Venting Flames (EVF) characteristics, the compartment thermal conditions were also investigated. Towards this end, 5 K-type thermocouples, located at different heights at the geometrical centre of the compartment (x = - 457.5 mm), were used to monitor the temperature profile developing at the interior of the fire compartment. The recorded thermocouple data, obtained at the interior of the compartment, were corrected for radiation using a "post-processing" methodology [9]. The coordinates of all sensors installed at the compartment-façade test facility are depicted in Figure 3. It is noted that the axis origin (x = 0, z = 0) corresponds to the point where the external façade surface meets the window lintel, at the centreline of the opening.

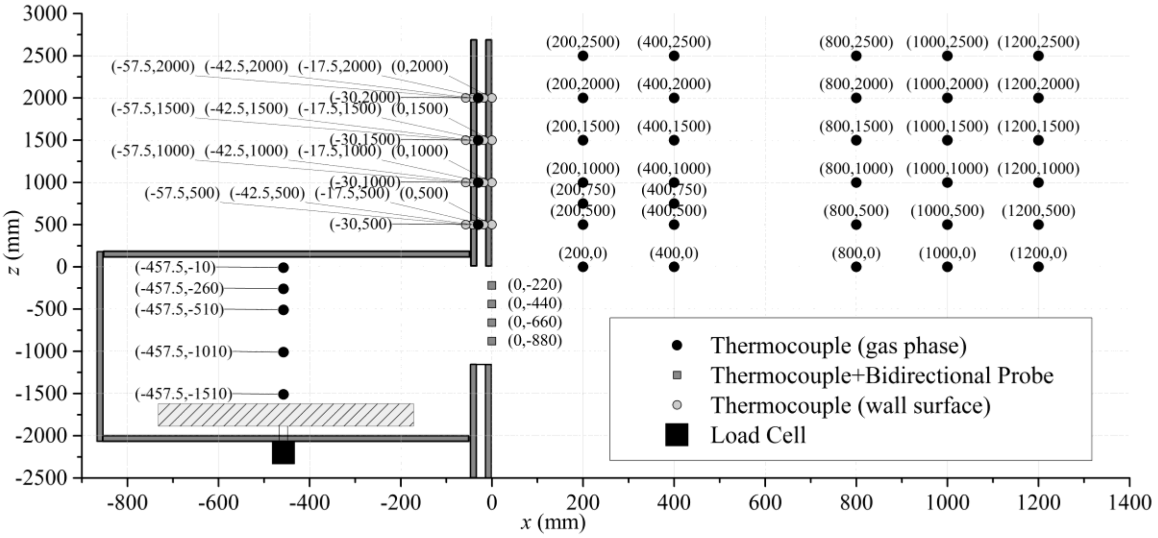

Figure 3. Locations of the sensors installed at the compartment-façade test facility.

Figure 3 depicts also the positioning of the thermocouples at the main layer interfaces of the VF system. Measurements were obtained at four different heights (0.5 m, 1.0 m, 1.5 m and 2.0 m above the lintel) for 5 positions across the VF system. More specifically, thermocouples were installed at the exposed surface of the external panel cladding (x = 0 mm, plaster coating layer), the unexposed side of the external panel cladding (x = - 17.5 mm, cement boards), the half-width of the air cavity (x = - 30 mm), the exposed side of the main façade (x = - 42.5 mm, gypsum plasterboard) and the unexposed side of the main façade (x = - 57.5 mm, gypsum plasterboard).

In addition, velocity measurements of the gaseous mixture entering and exiting the fire compartment through the window were acquired using a vertical array of four bidirectional probes located at the centreline of the window, supplemented by 4 K-type thermocouples located at the same positions

(Figure 3). This arrangement allowed the velocity values measured by the bi-directional probes to be temperature-compensated. Bidirectional probes measure the flow velocity of a fluid using a pressure differential. The probe consisted of a section of a 22 mm diameter circular stainless steel tube, with a barrier installed 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, whereas the downstream chamber senses a pressure slightly below the static pressure of the flow. This device, in addition to being as rugged as a stainless steel pitot-static tube, possesses certain features that render it ideal for fire research applications. Owed to its symmetric arrangement, a bidirectional probe is able to measure flow velocities in either direction, thus making it ideal for measurements without prior knowledge of flow direction (e.g. an opening in a fire compartment). The probe responds correctly when the flow at a point reverses its direction, e.g. when the opening neutral plane is lowered as the fire compartment is filled during the build-up of a fire. In addition, bidirectional probes exhibit angular insensitivity (measurements are considered to be 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. The pressure sensing lines, using silica hoses, were fed to Omega PX277-0.1D5V differential pressure transducers, which in turn were connected to the data logger. Data processing of the raw bi-directional velocity probe data was performed using the methodology presented by McCaffrey and Heskestad [10] on the design and calibration of bidirectional low-velocity probes for flame and fire applications.

Variations in flame shape and position were recorded using 2 video cameras. The first was positioned opposite the facade at a distance of 8.60 m, whereas the second was located at a right angle to the facade at a distance of 9.40 m. Both cameras were recording at 30 frames per second. A thermal camera was also positioned 8.60 m away from the façade, recording additional information regarding the thermal response of the external façade surface.

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. All measurements (temperature, velocity, fuel mass loss rate) were recorded using a universal data logging Interface designed in the LabView software; the sampling frequency was 1.0 Hz. The obtained measurements provided a detailed physical description of the main characteristics of the turbulent and reactive flow-field developing inside and outside the test compartment, as well as at the various layers of the VF system.

4. EXPERIMENTAL RESULTS

4.1. Fire Compartment (Indoors)

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 [11,12]. The combustion rate (or fire power) can be estimated by employing the fuel's mass loss rate (MLR). The instantaneous MLR was estimated by measurements of fuel mass (Figure 4). An almost constant fuel combustion rate was observed throughout the duration of the fire test. The pool fire was found to burn steadily until it entered the fire decay stage after approximately 850 s. The rather noisy signal is attributed to the increased turbulence at the interior of the compartment and the high measurement frequency (1.0 Hz); time-averaged values are also reported in Figure 4 (right). Assuming an (ideal) 100% combustion efficiency and using the measured heating value of n-hexane, the average fire power during the fully developed fire stage (100-800 s) was calculated to be approximately 2.76 MW.

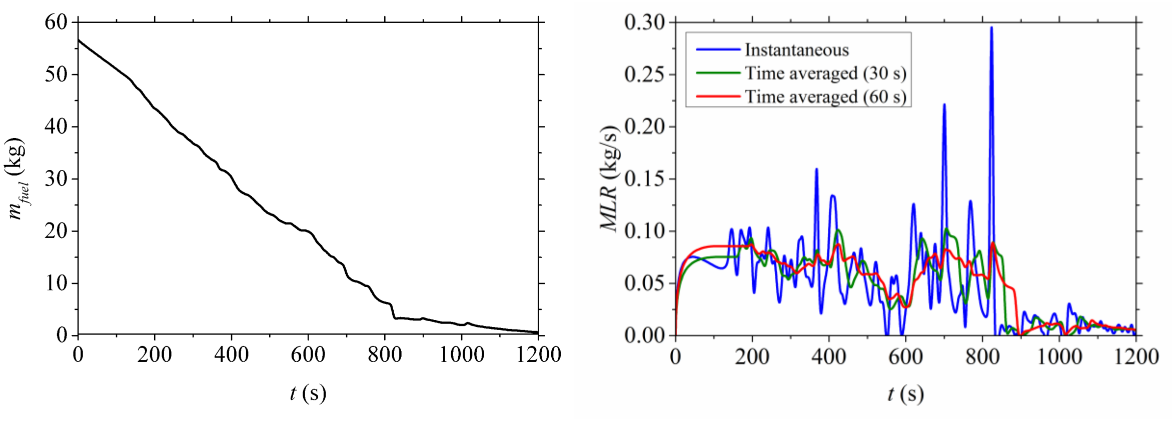

Figure 4. Measurements of fuel mass (left) and fuel mass loss rate (right).

The gas temperature evolution inside the compartment (x = - 457.5 mm) is depicted in Figure 5. The three characteristic stages of fire growth, fully developed fire and fire decay, typically encountered in compartment fires, can be easily identified. As expected, gas temperature values increase with increasing height; maximum values at the interior of the compartment reached 1100ºC. As shown in Figure 5, temperatures at all heights increase rapidly after ignition and only the temperature at the lowest position just above the fuel pan (-1510 mm) exhibits lower temperatures, approximately 600ºC, during the quasi-steady case. The decrease in temperature observed at 150-300 s is mainly attributed to ambient air entrainment through the lower part of the opening, as well as to the inclination of the flame. Generally, during the fully developed fire stage, gas temperatures at the interior of the fire compartment remained practically constant, exhibit slight fluctuations due to the severely turbulent flow-field established inside the compartment.

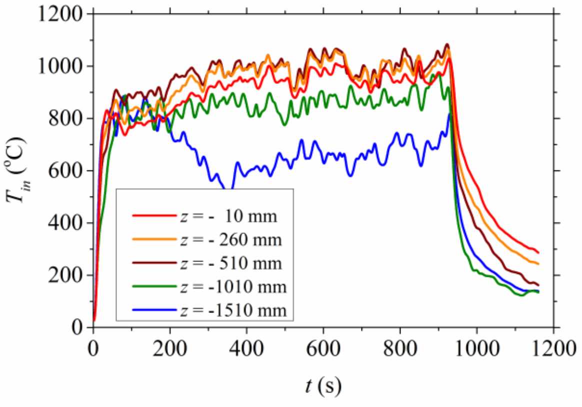

Figure 5. Temporal evolution of temperatures at the interior of the compartment at various heights.

4.2. Fire Compartment Opening

Velocity measurements at the centreline of the window at four positions, 220, 440, 660 and 880 mm below the window lintel are depicted in Figure 6 (left). Positive values, recorded constantly at the two measurement locations closest to the window lintel (-220 mm and -440 mm), correspond to gaseous combustion products, unburnt fuel and smoke exiting through the upper part of the opening. Negative velocity values, recorded close to the window sill (-880 mm) suggest ambient air entrainment into the fire compartment through the lower part of the opening. Velocities measured at a distance of 0.66 from the window lintel do not exhibit a consistent sign, being sporadically either positive or negative, thus suggesting that this location is close to the opening's neutral plane. Peak combustion products exit velocities reach 4 m/s, whereas air entrainment velocities are, generally, not higher than 2 m/s. Intense velocity fluctuations are observed both in the entering and exiting flows;

these are mainly attributed to the turbulent characteristics of the flow, as well as to the ever-changing ambient conditions (external wind velocity magnitude and direction). Temperatures of the exiting combustion products and EVF close to the window lintel (-220 mm) were found to exceed 900°C, whereas air entrainment temperatures close to the window sill (-880 mm) were slightly higher than the ambient temperature (Figure 6, right).

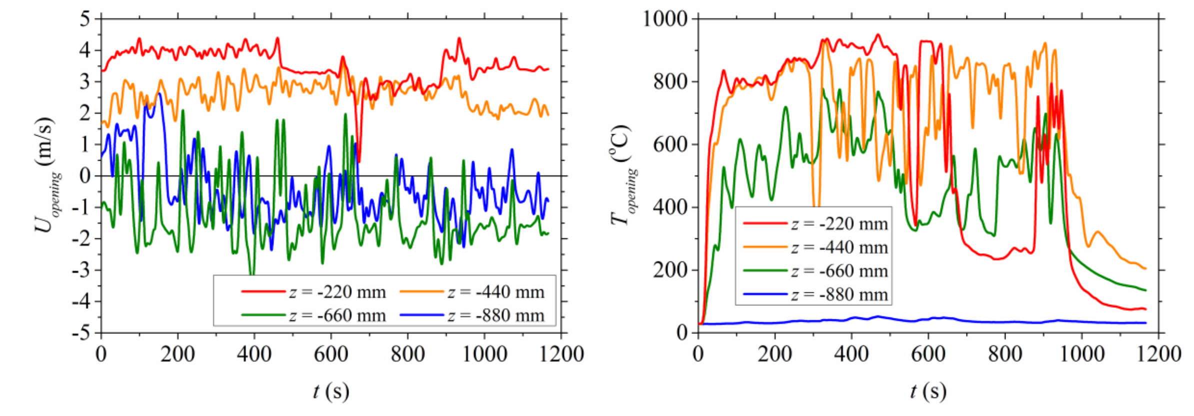

Figure 6. Temporal evolution of gas velocity (left) and temperature (right) at the centreline of the opening (x = 0 mm), at various heights.

4.3. Externally Venting Flame (Outdoors)

Indicative images of the EVF shape and dimensions at successive time steps are depicted in Figure 7. During the initial stages of fire development, where there is enough oxygen in the compartment (well-ventilated conditions), combustion is limited at the interior of the compartment. As soon as the oxygen is depleted (under-ventilated conditions), flames stretch in the horizontal direction, gradually moving towards the opening. At approximately 120 s after fire initiation, flames start emerging from the opening, quickly establishing a distinct EVF. During the latter stage, the EVF shape and dimensions are highly fluctuating, being affected by the ever-changing external wind velocity direction and magnitude.

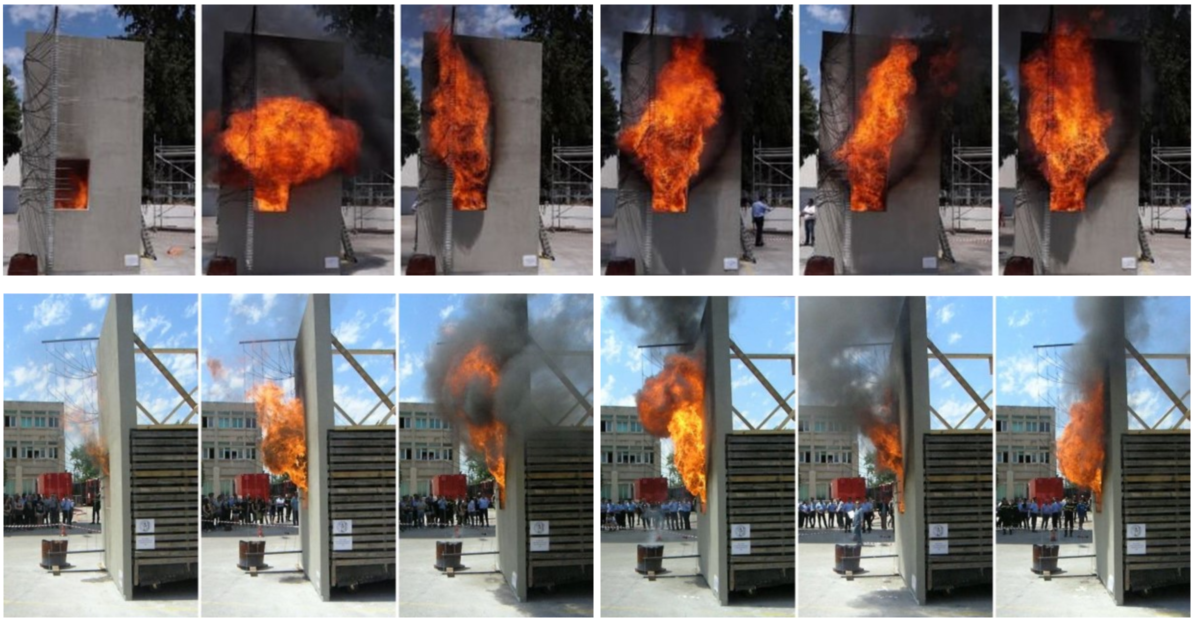

Figure 7. EVF development at 2.5 min intervals; front view (top) and side view (bottom).

Flames are projected from the fire compartment through the upper half of the opening, at an angle of approximately 45° to the horizontal plane; subsequently, they bend upwards (Figure 7, bottom). At specific instances, due to peripheral air entrainment and external wind, the EVF tends to curl back and impinge upon the exposed façade surface. The EVF acts as a heat source. Radiative and convective heat transfer to the façade, due to EVF, the impinging flames and the hot combustion products, results in high temperatures observed at the exposed surface, which may reach even 500°C (Figure 8).

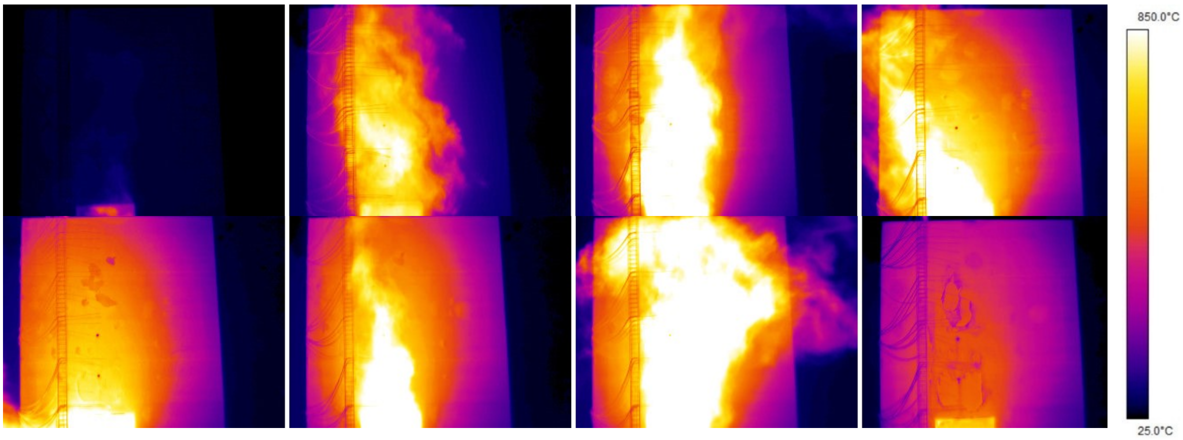

Figure 8. Infrared images of the exposed façade surface at 2.5 min intervals.

Temperature contour plots shown in Figure 9 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. Three characteristic instances are presented, at 210 s (initial stage), 630 s (fully-developed EVF) and 840 s (fire decay stage) after fire initiation, in order to assess the EVF characteristics throughout the duration of the fire event. As expected, peak temperature values, up to 900°C, are observed at the vicinity of the opening, close to the façade surface (x = 0 m), at a region just above the window lintel (z = 0.0 – 1.0 m), where the EVF is established (c.f. Figure 7). EVF temperatures gradually decrease with increasing height and distance from the opening.

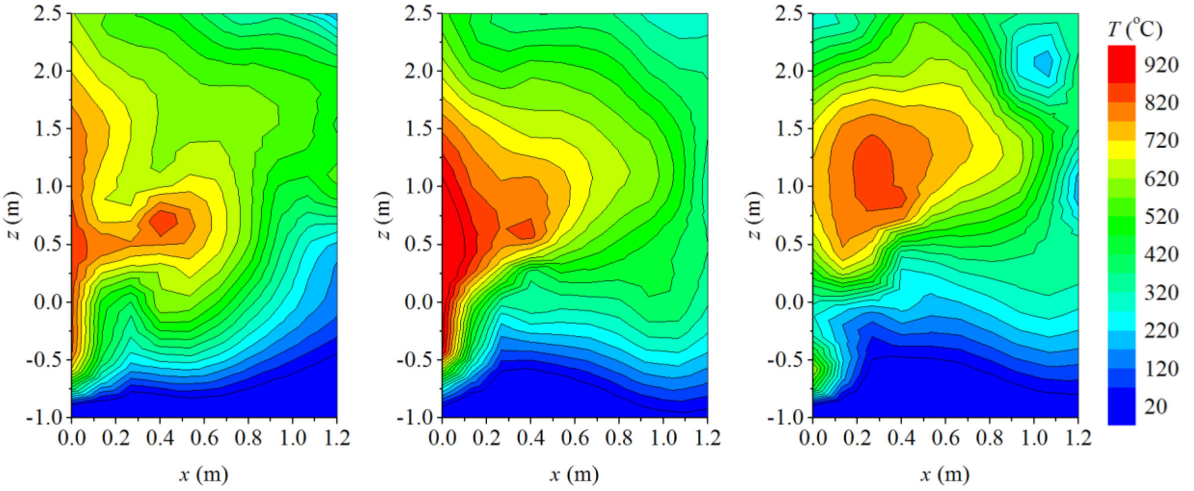

Figure 9. Outdoor temperature contours at the centreline plane perpendicular to the façade, 210 s (left), 630 s (middle) and 840 s (right) after fire initiation.

4.4. Ventilated Façade System

The temporal evolution of the temperature measurements at various VF system interfaces is depicted in Figure 10. The temperature of the unexposed side of the VF system (x = - 57.5 mm) in all measurement locations increased slowly during the first 200 s and remained practically 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 180ºC [13]. By employing this failure criterion, the VF system proved to effectively sustain the 900 s fire exposure, since the temperature of the unexposed side (x = - 57.5 mm) did not surpass 180ºC in any measurement position. Furthermore, gypsum plasterboards exposed to fire are considered to exhibit mechanical failure when cracks or openings are observed through the wall [14]; after the fire test, no visual observation of cracks was made at the internal façade wall (gypsum plasterboard).

Temporal profiles of temperatures across the various layers of the VF system exhibit similar qualitative characteristics for all measurement heights. In general, temperatures are constantly increasing until shortly after the end of the fully-developed fire stage (850 s), when the EVF is diminished and temperatures at the VF system begin to decrease. As expected, maximum temperature values are observed at the exposed surface (x = 0 mm), whereas they are gradually decreased with increasing distance from the façade face ($x < 0$ mm).

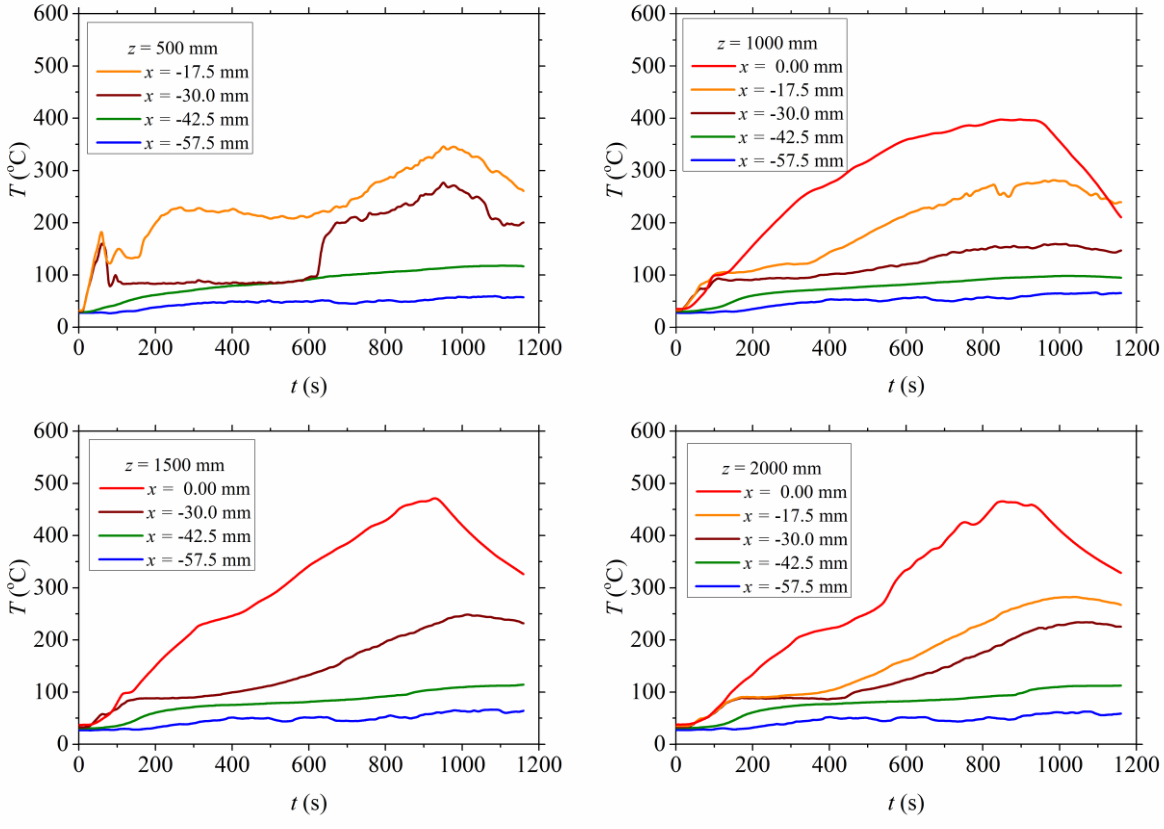

Figure 10. Temperature measurements at the various interfaces of the VF system, at a height of 0.5 m (top left), 1.0 m (top right), 1.5 m (bottom left) and 2.0 m (bottom right) above the window lintel.

In Figure 11 (left), temperature measurements at various heights along the exposed side of the external cladding panel (x = 0 mm) are depicted. It is evident that the thermal field developing due to the emergence of the EVF (c.f. Figure 9) imposes a severe thermal loading on the exposed façade surface. However, due to the multi-layered construction of the VF system temperatures at both faces of the "main" façade (x = - 42.5 mm and x = - 57.5 mm) remain lower than 140ºC in all cases, thus suggesting that the VF system essentially protects the building façade from direct exposure to the emerging EVF.

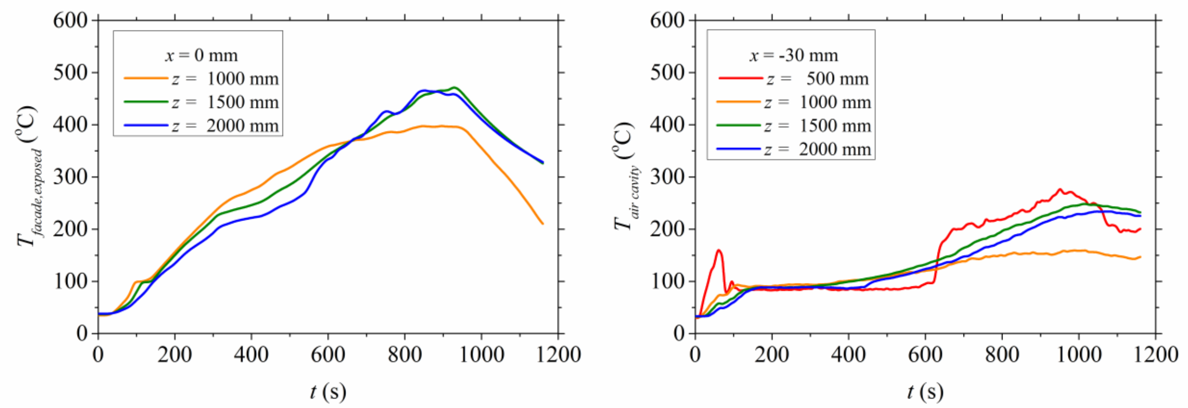

Figure 11. Measurements of exposed façade wall surface temperature (left) and gas temperature at the middle of the air cavity (right).

Gaseous temperature measurements along the height of the air cavity are depicted in Figure 11 (right). It is evident that even though combustion products and unburnt fuel vapours may manage to enter the air cavity, no consistent flaming is observed. Gas temperatures inside the cavity are gradually increasing, being less than 100ºC for the first 8 min (480 s). Temperatures at the lowest measuring position (z = 500 mm) reach 280ºC shortly after the end of the fully-developed fire stage; this may be attributed to the partial failure of the perforated metal inset used at the bottom opening of the air cavity close to the window lintel. The reported temperature measurements, assisted by visual observations during the fire test, suggest that the air cavity of the VF system does not assist flame spreading along the vertical direction.

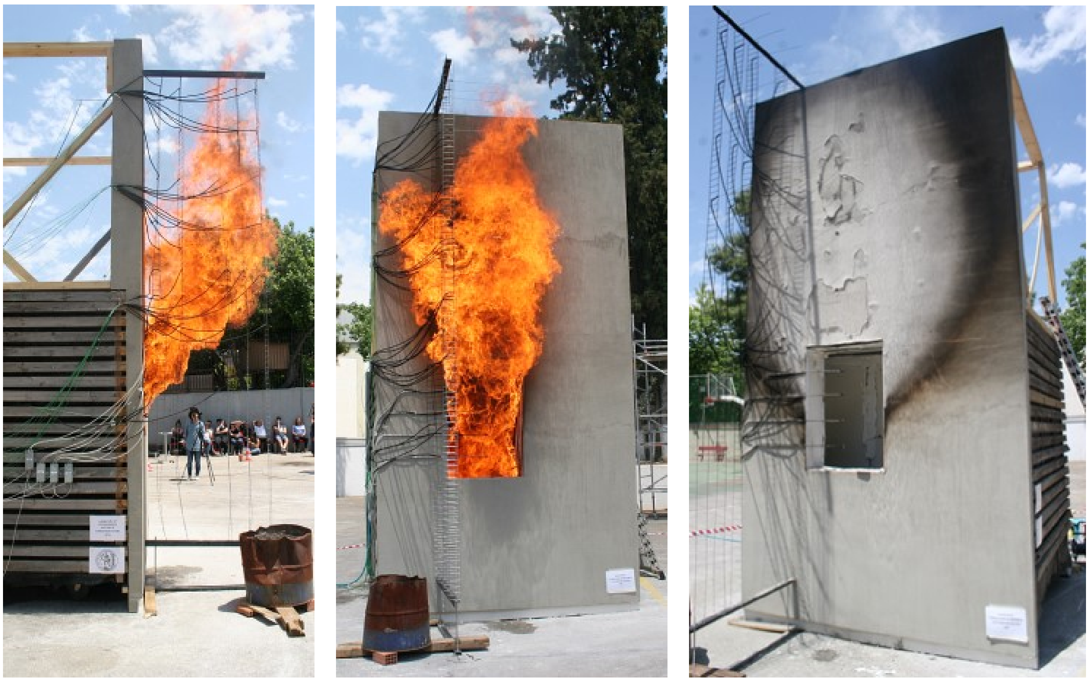

Figure 12. Indicative photographs of the compartment-façade facility during (left, middle) and after (right) the fire test.

5. CONCLUDING REMARKS

The ventilated façade (VF) system is a double-wall construction, comprising an external lightweight cladding panel and the building's existing façade, which is used to increase indoor comfort levels (e.g. temperature, humidity) in buildings. 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 emerging externally venting flames. Aiming to investigate the fire behaviour of a typical VF system, a large scale compartment-facade fire test has been carried out (Figure 12). An extensive set of sensors has been installed both inside and outside the test compartment, aiming to record the temporal variation of several important physical parameters, such as gas and wall surface temperatures, gas velocities and fuel mass loss rate. Emphasis has been given on the estimation of the thermal characteristics of the externally venting flames, emerging close to the facade, since these are the main physical parameters affecting the heat exposure of the VF system. A commercial VF system has been employed; no thermal insulation has been used, aiming to investigate the main aerodynamic and thermal phenomena affecting the flow of hot gases and flames in the air cavity of the VF system. In addition, no fire barriers have been installed, thus representing a "worst case" scenario for a VF system with no combustible materials. Analysis of the experimental data suggested that even though gaseous combustion products have managed to penetrate into the air cavity of the VF system, no consistent flaming conditions have been established. In addition, wall surface temperatures on the unexposed side of the system have remained constantly below 180°C throughout the duration of the fire test. In conclusion, a VF system where no combustible materials are used (e.g. thermal insulation) essentially protects the existing building façade and it does not enhance fire spreading in the vertical direction.

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. It can be also used to validate CFD models or evaluate the accuracy of fire engineering design correlations currently available.

ACKNOWLEDGEMENTS

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