



Experimental investigation of Externally Venting Flames in under-ventilated compartment fires

Asimakopoulou, E., Kolaitis, D., & Founti, M. (2015). *Experimental investigation of Externally Venting Flames in under-ventilated compartment fires*. Paper presented at Fire and Materials 2013.

[Link to publication record in Ulster University Research Portal](#)

Publication Status:

Published (in print/issue): 01/01/2015

Document Version

Author Accepted version

Document Licence:

Unspecified

General rights

The copyright and moral rights to the output are retained by the output author(s), unless otherwise stated by the document licence.

Unless otherwise stated, users are permitted to download a copy of the output for personal study or non-commercial research and are permitted to freely distribute the URL of the output. They are not permitted to alter, reproduce, distribute or make any commercial use of the output without obtaining the permission of the author(s).

If the document is licenced under Creative Commons, the rights of users of the documents can be found at <https://creativecommons.org/share-your-work/licenses/>.

Take down policy

The Research Portal is Ulster University's institutional repository that provides access to Ulster's research outputs. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact pure-support@ulster.ac.uk

EXPERIMENTAL INVESTIGATION OF EXTERNALLY VENTING FLAMES IN UNDER-VENTILATED COMPARTMENT FIRES

Eleni K. Asimakopoulou*, Dionysios I. Kolaitis and Maria A. Founti

Laboratory of Heterogeneous Mixtures and Combustion Systems, Thermal Engineering Section,
School of Mechanical Engineering, National Technical University of Athens
9 Heroon Polytechniou St., Polytechnioupoli Zografou, Athens 15780, Greece
*e-mail: elasimak@mail.ntua.gr

ABSTRACT

In a compartment fire, Externally Venting Flames (EVF) may significantly increase the risk of fire spreading to adjacent floors or buildings, especially now-a-days that there is an ever-increasing trend of using combustible insulation materials in building façades. The main scope of this work is to investigate the fundamental physical phenomena governing EVF development. In this frame, a series of medium-scale fire compartment experiments is performed, utilizing a ¼ scale model of the ISO 9705 compartment, equipped with an extended façade. Recording of the dynamic behaviour of EVF is carried out using a selectively installed sensor network that allows measurement of important physical parameters, such as flame envelope geometry, gas and wall surface temperatures, façade heat flux, fuel mass loss and gas species concentrations. A dedicated image-processing tool is developed, aiming to record the dynamic development of the flame envelope (e.g. height, width, volume). A range of realistic fire scenarios, relevant to building fires, is implemented as part of the experimental campaign. An “expendable” fuel source (n-hexane liquid pool fire) is utilized to effectively simulate realistic building fire conditions. A parametric study is performed by varying two important physical parameters, i.e. fire load and opening dimensions. Experimental results suggest that the flame geometry and EVF duration are mainly affected by the opening dimensions, whereas the fuel load has a significant impact on the heat flux to the façade. An increasing number of recent reports suggest that existing fire engineering design methodologies cannot describe with sufficient accuracy the characteristics of EVF under realistic fire load conditions. In this context, the obtained experimental data are used to assess a range of fire engineering design correlations, commonly used to estimate the centreline temperature of the EVF plume and the heat flux to the adjacent façade surface. The obtained extensive set of experimental data can be used to validate CFD fire models or to evaluate the accuracy of available fire engineering design correlations.

1. INTRODUCTION

Externally Venting Flames (EVF) may occur in cases of fully developed compartment fire depending on fuel and oxygen availability. If a compartment fire becomes under-ventilated, due to insufficient “fresh” air entrainment through the compartment openings, flames may emerge through openings (e.g. windows) and extend over the external building façade. The resulting EVF is prone to curl back and impinge upon the wall above the opening, due to peripheral air entrainment, generating strong convective and radiation heat fluxes to the façade wall. The façade surface absorbs heat from the plume, but restricts the air entering from the wall side; the wider the opening the closer the plume is to the wall. Thermal radiation depends strongly on the flame emissivity, a quantity that cannot be calculated a priori for buoyant, turbulent, diffusion flames^{1, 2}. The total heat flux density due to the

EVF can be high enough to create a fire hazard to the storeys above, as demonstrated in recent fires in high-rise buildings³.

Due to the increasing trend of using combustible insulation materials in building façades for energy performance purposes³, EVF may pose a significant risk of fire spreading from the fire origin compartment to adjacent floors or buildings. However, the majority of fire safety codes are lacking specific methodologies to evaluate the risks associated with EVF, since new façade design requirements and construction materials challenge the established fire safety solutions. There is an alarming occurrence of recent EVF events in high-rise buildings, resulting in a large number of casualties, structural damage and property loss³, a fact that renders the need to improve design guidelines for EVF and façade fires an urgent priority.

Extensive fundamental research has been performed during the past years on EVF characteristics and heat flux in external façades, which has led to better understanding of flow and thermal characteristics of EVF. Research on EVF, focused on identifying the main physical parameters governing internal fire dynamics and consequent EVF, commenced in the early 1960's by Yokoi¹ and was further expanded by others^{1,4,5}. Some findings of the respective research regarding EVF description and its impact on façades have been gradually incorporated in fire safety codes and design guidelines. The Eurocode design guidelines⁶, currently implemented in the E.U., provide general principles and rules regarding thermal and mechanical actions on structures exposed to fire; fire actions for designing load-bearing structures are prescribed in EN 1991 (Eurocode 1)⁶. However, fire spreading due to combustible façade materials is not directly addressed in the Eurocode guidelines and there is only a coincidental reference to risks associated with EVF (i.e. protection of steel and timber building elements).

An increasing number of recent reports⁷⁻¹¹ suggest that existing fire engineering design methodologies cannot describe with sufficient accuracy the characteristics of EVF under realistic fire load conditions. The main scope of this work is to comparatively assess fire engineering design correlations used to describe centreline temperatures of EVF plume and heat fluxes to adjacent façade walls^{5,6,12}. The predictive accuracy of each correlation is evaluated through comparison with experimental data obtained in a medium scale compartment-façade fire arrangement, using a variety of fire load levels and opening factor values. Numerous methodologies have been presented over the years; the widest range of applicability can be attributed to the ones developed by Law¹³ and Oleszkiewicz⁴ and thus they will be used as groundwork for the analysis currently presented.

2. FIRE ENGINEERING DESIGN CORRELATIONS RELATED TO EVF

Externally Venting Flames are essentially flames that traverse an opening of the fire compartment and emerge to the ambient environment. The interior fire plume is the principal mass transfer mechanism between hot and cold layers, progressing buoyant flows through vents of the fire compartment^{10,13}. Incoming air enters the fire compartment through the lower part of the opening, whereas hot, vitiated, unburnt gases leave the fire compartment through the upper part of the opening. Depending on the size of the compartment and the fire load, it is possible to have a fire plume that cannot be contained within the compartment, resulting in flame extension to the ambient environment. In addition, under oxygen deficiency conditions (under-ventilated fire), external burning of fuel rich gases leaving the fire compartment may occur, further sustaining EVF development^{3,5}. As soon as the EVF plume turns upwards, air entrainment becomes significant, advancing combustion and dilution processes.

2.1 EVF Centreline Temperature

There are various methodologies available to estimate the temperature (T_0) of the plume that emerges through the opening. The early work of Yokoi¹ regarding the temperature distribution of upward currents from a circular heat source, revealed the importance of a range of parameters, such as the equivalent radius of the opening (r_0), opening height (Z_0) and heat release rate (Q). However, the effects of the thermal properties of the façade wall materials to the gas temperature distribution of the EVF were neglected. The proposed correlations, based on a modified vorticity transfer theory for upward currents in cases of point, line and rectangular heat sources, indicated a strong dependence of the centreline temperature to the $2/3$ power of the heat release rate. As soon as the plume turns upwards, air entrainment becomes significant, advancing combustion and dilution processes. Further investigation based on medium- and large- scale compartment-façade fire experiments^{5, 13}, determined a range of parameters affecting the EVF behaviour, such as radiative effects¹⁴, air mass flow rate inside the compartment⁵ and forced ventilation conditions^{7, 8, 13}. Investigating a broad range of semi-empirical correlations used to estimate the centreline temperatures of fire plumes and ceiling jets, Beyler¹⁴ determined their range of applicability using uncertainty analysis. The general trend is that flame temperature is directly proportional to the distance along the centreline of the EVF; this has been indicated in the fundamental work of Law¹³ and is implemented in Eurocode 1⁶. A more general approach was considered by Himoto¹⁰, employing a two-dimensional analysis and experimental validation.

A range of semi-empirical correlations, proposed by various investigators to estimate the EVF centreline temperature rise above the ambient temperature, $\Delta T_m = T_0 - T_{amb}$, is shown in Table 1. In some cases, e.g. T3¹ and T4¹⁰, condensed expressions are derived by applying commonly used values for the physical properties of the ambient and warm air (ρ_{amb} , C_p , T_{amb}). The value of z used in the presented correlations corresponds either to the height above the opening spandrel (T1, T3 and T4)^{10, 1, 6} or the height above the virtual source (T2)¹⁴. There are various methodologies available to estimate the temperature (T_0) of the plume exiting through the opening^{6, 13, 14}, which appears in correlation T1.

Table 1: Semi-empirical correlations for estimation of the EVF centerline temperature rise above the ambient temperature.

Abbr.	Range	Original Correlation (ΔT_m)	“Condensed” Expression (ΔT_m)
T1 ⁶	-	$\left(1.0 - 0.4725 \frac{W_0 l}{Q}\right) (T_0 - T_{amb})$	-
T2 ¹⁴	-	$24.6 Q^{2/3} z^{-5/3}$	-
T3 ¹	$\frac{z}{r_0} \leq 0.3$	$2.0 \frac{Q^{2/3}}{C_p \rho_{amb}^{2/3} g^{1/3} T_{amb}^{-1/3} (H_0 - z_n)}$	$25.01 Q^{2/3} (H_0 - z_n)^{-1}$
	$\frac{z}{r_0} > 0.3$	$\frac{0.00193 \left(\frac{z}{r_0}\right) Q^{2/3} r_0^{-5/3}}{C_p \rho_{amb}^{2/3} g^{1/3} T_{amb}^{-1/3}}$	$0.024 Q^{2/3} z [W_0 (H_0 - z_n)]^{-8/3}$
T4 ¹⁰	$\frac{z}{H - z_n} \leq 0.64$	$2.0 \frac{Q^{2/3}}{C_p^{2/3} \rho_{amb}^{2/3} g^{1/3} T_{amb}^{-1/3} (H_0 - z_n)}$	$25.01 Q^{2/3} (H_0 - z_n)^{-1}$
	$0.64 \leq \frac{z}{H - z_n} \leq 2.4$	$1.6 \frac{Q^{2/3} z^{-1/2}}{C_p^{2/3} \rho_{amb}^{2/3} g^{1/3} T_{amb}^{-1/3} (H_0 - z_n)^{1/2}}$	$20.01 Q^{2/3} z^{-1/2} (H_0 - z_n)^{-1/2}$
	$2.44 \leq \frac{z}{H - z_n}$	$2.5 \frac{Q^{2/3} z^{-1}}{C_p^{2/3} \rho_{amb}^{2/3} g^{1/3} T_{amb}^{-1/3}}$	$31.26 Q^{2/3} z^{-1}$

2.2 Heat Flux on the Façade

The heat balance in a façade surface exposed to EVF was initially expressed in the pioneering work of Law¹³, who reviewed and analysed a large number of cellulosic compartment fires, Layout I (Figure 1). The formulated methodology incorporates calculation of convection and radiation net heat fluxes from the EVF, openings and surroundings, under steady state conditions, aiming to derive a conservative solution regarding the heat transfer to external steel surfaces. Although this methodology has been developed in order to assess the structural integrity of external steel elements engulfed or not in flames, it is known to have wider applications⁹.

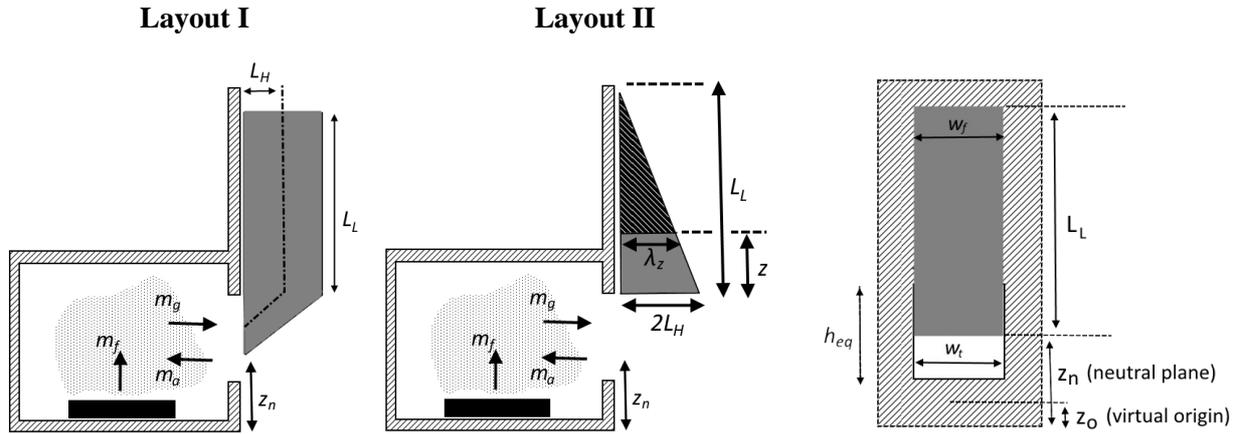


Figure 1. General schematic illustrating the main characteristics of EVF.

If the façade surface exposed to a fire is located outside the convective stream of flame and hot gases, in case there are no openings on opposite sides of the compartment or air flow from another source, the heat balance at a point in the façade can be expressed using Eq. (1). In order to estimate the heat flux on the façade it is necessary to estimate the convective heat transfer coefficient (a_c), the emissivity (ε) and the effective temperature of the flames (T_f).

$$q'' = q''_{conv} + q''_{rad} = a_c (T_z - T_{wall}) + \varepsilon_z \phi_f \sigma T_z^4 + \phi_f \sigma T_f^4 - \sigma T_{wall}^4 \quad [1]$$

The configuration factor (ϕ_f) of the opening in relation to the surface depends on the size and shape of the opening and the position of the surface; methodologies for estimation of configuration factors are given in standard radiative heat transfer textbooks^{6, 15}. The two last terms in Eq. (1), expressing the radiative heat transfer from the compartment flames through the opening ($\phi_f \sigma T_f^4$) and the radiative heat loss from the façade wall to the surroundings (σT_{wall}^4), are usually neglected. The local emissivity of the flame (ε_z) is calculated using a constant extinction (or emission) coefficient (k) (usually valued 0.3 m^{-1}) and constant flame thickness ($\lambda_z = 2L_H$), as depicted in Figure 1 (Layout I), using Eq. (2).

$$\varepsilon_z = 1 - \exp(-k\lambda_z) \quad [2]$$

By assuming that flames and hot gases leave the compartment at approximately 2/3 of the height of the opening, Eq. (3) can be used for the calculation of the convective heat transfer coefficient (a_c), taking into account the shape of the receiving surface via appropriate length scales e.g. their geometrical characteristics. In the original paper of Law¹³, it is not clear how the definition of characteristic length scales (e.g. d_{eq}), apply to a point on the façade, since it is defined as the average

of the two main dimensions of the cross-section of a steel member. As stated in a previous work⁹, the characteristic length scale when referring to a point on the façade can be taken as the vertical distance between the opening soffit and the point itself. The determination of the empirical factor c is based on experimental measurements obtained from wood crib fires conducted in medium-scale fire compartments¹³; usually, a value of $c = 4.67$ is used.

$$a_c = c \left(\frac{Q}{A_v} \right)^{0.6} \left(\frac{l}{d_{eq}} \right)^{0.4} \quad [3]$$

However, this conservative assumption is not adequate for the calculation of heat transfer in the area near the top of the flame⁴. Thus, a modified version of the Law methodology was presented by Oleszkiewicz in his analysis on heat transfer from an opening plume to a building façade⁴. In the original implementation of the Law methodology, the flame thickness is assumed constant (c.f. Figure 1, Layout I), leading to miscalculations in the area near the top of the flame. In order to avoid such behaviour, Oleszkiewicz introduced a triangular shaped flame shown in Figure 1 (Layout II). The suggested method is based on the calculation of the incident heat flux of the EVF to the vicinity of the façade^{4,16}, as expressed in Eq. (1), assuming a unity configuration factor. The local emissivity of the flame (ε_z), Eq. (2), is calculated using a constant extinction coefficient regardless of the fuel type, as recommended by previous methodologies¹³, and flame thickness assuming triangular EVF shape⁴, as shown in Eq. (4). By assuming that the convective heat transfer coefficient is related to the ratio of the burning rate to the opening area, Eq. (3) is used by eliminating the term associated to the shape of the receiving surface⁴ ($l/d_{eq}=1$).

$$\lambda_z = \frac{2 L_H (L_L - z)}{L_L} \quad [4]$$

2.3 Heat Flux Calculation Methodologies

There exist a range of different methodologies for the determination of heat fluxes from EVF. Usually, EVF are modeled as vertical planes and their heat flux is mainly influenced by the fire compartment geometry, HRR, ambient conditions (such as temperature and wind speed) and compartment temperature^{4,7,8,13,17}. In various heat flux calculation methodologies, including the Eurocode 1⁶, it is suggested to use predefined values for the extinction (k) and convection heat transfer (α_c) coefficients of exposed and unexposed members and types of fire curves, regardless of the type of the fuel, its burning rate and the EVF geometric characteristics. In the current work, the impact of a range of such parameters that may actually influence the EVF's thermal impact to the façade, namely the EVF shape, the fuel type effect on the extinction coefficient and the appropriate use of the convective heat transfer coefficient are investigated. Aiming to establish a rigorous methodology for the estimation of the heat flux hazard to external façade elements, a range of different methodologies are assessed (c.f. Table 2); their predictions are assessed using measurements obtained in the medium-scale fire tests.

The emissivity of the EVF (ε_f) depends on the flame thickness, so the effect of EVF geometry is initially investigated [Methods HF1 and HF2] by implementing two widely applied flame shapes; namely an EVF with a constant^{6,13} flame thickness (Figure 1, Layout I), and a triangular-shaped EVF⁴ (Figure 1, Layout II). Another factor influencing flame emissivity is the extinction coefficient (k); although in the majority of the available methodologies it is assumed constant^{4,6,13}, usually equal to 0.3 m^{-1} , in realistic fire scenarios this is not the case^{15,18}. Aiming to investigate the effect of the extinction coefficient on the overall heat flux estimation, a value of 12.0 m^{-1} , appropriate for the hexane fuel used in the tests^{13,15}, is used [Method HF3]. Finally, the impact of the convective heat transfer coefficient (α_c), using a conservative approach of general applicability [Method HF4] or a correlation taking into account the EVF height [Method HF5], is evaluated. In all the examined

methodologies, heat flux levels are estimated using Eq. (1) by assuming $\phi_f = 1$ and neglecting the last two terms of the heat balance equation⁴; calculation of the EVF centreline temperature (T_z) is based on correlation T1^{6,13}.

Table 2: Methodologies for estimation of heat flux to the façade.

Abbr.	Heat Flux			Flame Shape
	Radiative Component	Convective Component	a_c (W/m ² K)	Figure 1
	λ_z	k		
HF1	$2L_H$	0.3	Eq. (3)	Layout I
HF2	Eq. (4)	0.3	Eq. (3)	Layout II
HF3	$2L_H$	12.0	Eq. (3)	Layout I
HF4	$2L_H$	0.3	25	Layout I
HF5	$2L_H$	0.3	Eq. (3), $l/d_{eq}=1$	Layout I

3. EXPERIMENTAL WORK

3.1 Medium-scale Compartment-Façade Configuration

A series of fire experiments were conducted in a medium-scale compartment-façade fire apparatus. The compartment was a 1/4 scale model of an ISO 9705 compartment¹⁸. The internal compartment dimensions were 0.60 m x 0.90 m x 0.60 m; the external façade wall measured 0.658 m x 1.8 m. A double layer of 0.0125 m thick fireproof gypsum plasterboards was used as an internal and external lining material. The fire compartment opening, located in the middle of the north wall, measured 0.20 m x 0.50 m. A schematic (side view and ground plan) of the experimental apparatus and a characteristic photograph depicting the locations of the measuring devices are shown in Figure 2.

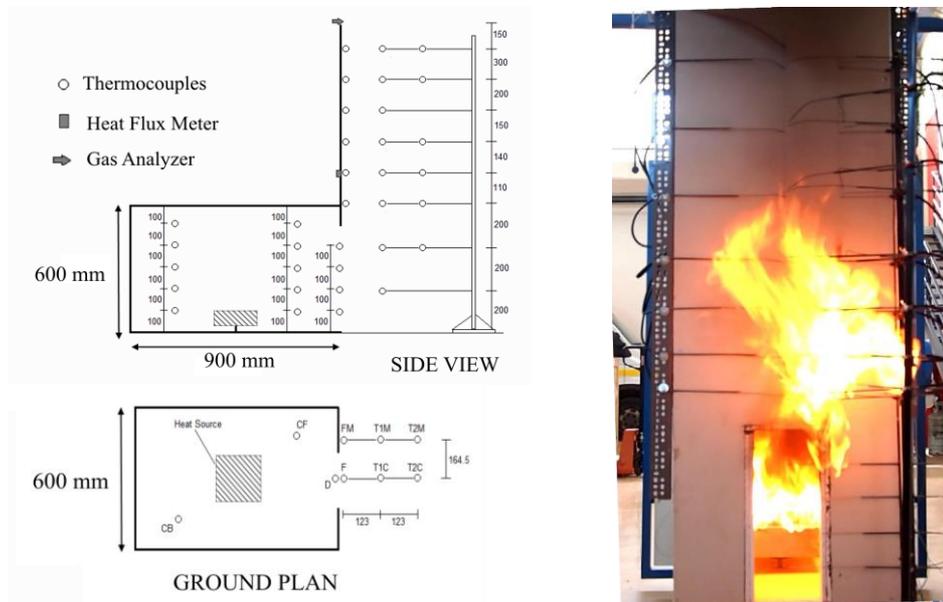


Figure 2. General layout (left) and a characteristic photograph (right) of the medium-scale compartment-façade fire apparatus.

3.2 Measuring Devices

The overall thermal behaviour of the compartment-façade configuration was investigated by measuring temperatures and heat fluxes at various locations. 10 K-type thermocouples 1.5 mm in

diameter, located in the front and rear corner of the compartment and 4 thermocouples vertically distributed in the centreline of the opening were used to monitor the temperature profiles developing at the interior of the fire compartment. Emphasis was given to the characterization of the temperature environment adjacent to the façade wall along the height of the fire plume both in the centreline and off-axis positions (164.5 mm away from the centreline). Towards this end, 14 thermocouples were placed in various locations across the façade wall, whereas 27 additional thermocouples were distributed among two thermocouple trees, located at a distance of 123 mm and 246 mm from the façade wall, respectively (Figure 2). A water-cooled, 25 mm diameter, Schmidt-Boelter heat flux sensor was placed at the centreline of the façade surface facing the EVF, 110 mm above the opening. All thermocouples and heat flux measurements were recorded using a Universal Data Logging Interface designed in LabView software; the sampling frequency was 1 s. A thermal camera was positioned 6.0 m away from the apparatus facing the façade to record additional information regarding the thermal response of the façade surface. Two digital video cameras were positioned at two locations, opposite and at a right angle to the opening, recording the developing EVF envelope, at 30 frames per second. Time series of video frames were obtained and processed using an in-house developed MATLAB code, aiming to determine the geometric characteristics of the EVF envelope¹⁹.

3.3 Parametric Studies: Fire Load and Opening Dimensions

Gaseous burners are commonly used in relevant fire compartment experiments^{4, 5, 20}, aiming to provide a constant (steady-state conditions) fire source. However, in order to achieve more “realistic” fire conditions, relevant to actual building fires, an “expendable” (transient conditions) fuel source was used. A stainless steel rectangular pan, measuring 0.25 m x 0.25 m x 0.10 m, was located in the geometrical centre of the compartment’s floor; n-hexane was used as the liquid fuel of choice. The mass of the fuel source was continuously monitored via a load cell, installed under the pan. The fuel pan size was selected in order to achieve under-ventilated fire conditions, thus facilitating the emergence of EVF.

A parametric study was performed, by varying the total fuel load (test cases 1, 2 and 3) and the opening dimensions (test case 4); the fire load used in test case 4 was identical to the fire load used in test case 2. A summary of the main operational parameters, i.e. opening height (H_v), opening width (W_v), ambient temperature (T_∞) and relative humidity (RH_∞), total fire duration (t_{dur}), fuel mass (m_f), global equivalence ratio (GER)¹⁵, total heat release rate (Q), average heat release rate in the interior of the fire compartment ($Q_{ins,m}$) and excess heat release rate (Q_{ex})⁵, for the 4 test cases examined, is given in Table 3. Test cases 2, 3 and 4 corresponded to under-ventilated fire conditions; in test case 1, a slightly over-ventilated fire was developed, due to the low fire load used.

Table 3. Summary of main operational parameters for the examined test cases.

Test case	H_v (m)	W_v (m)	T_∞ (°C)	RH_∞ (%)	t_{dur} (s)	m_f (kg)	GER (-)	$Q_{ins,m}$ (kW)	Q_{ex} (kW)
1	0.5	0.2	25.8	42.0	372	0.655	0.735	-	-
2	0.5	0.2	26.7	42.0	525	1.539	1.224	106.5	25.5
3	0.5	0.2	26.5	47.0	595	6.078	2.159	106.5	126.5
4	0.3	0.2	26.3	37.2	664	1.539	2.081	49.35	54.65

4. RESULTS AND DISCUSSION

4.1 Fuel Consumption Rate

The fuel consumption rate or combustion rate of pool fires in compartments 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 ^{2, 15}. These effects are illustrated in Figure 3, where measurements of the instantaneous fuel mass consumption rate for all the examined test cases are depicted. It is evident that higher initial fuel mass results in enhanced fuel combustion rates, (Figure 3, left). In addition, as time advances, the gradual lowering of the liquid fuel level results in a slight increase of the instantaneous fuel combustion rate. The size of the opening mainly affects the duration of the fire event (Figure 3, right); the burning period in test case 4 is prolonged due to the decreased ventilation factor. The pool fire is observed to burn steadily in both test cases 2 and 4, until it enters the decay stage after approximately 500 s and 650 s respectively. The rather noisy signal in test case 4 can be attributed to the increased turbulence in the interior of the fire compartment.

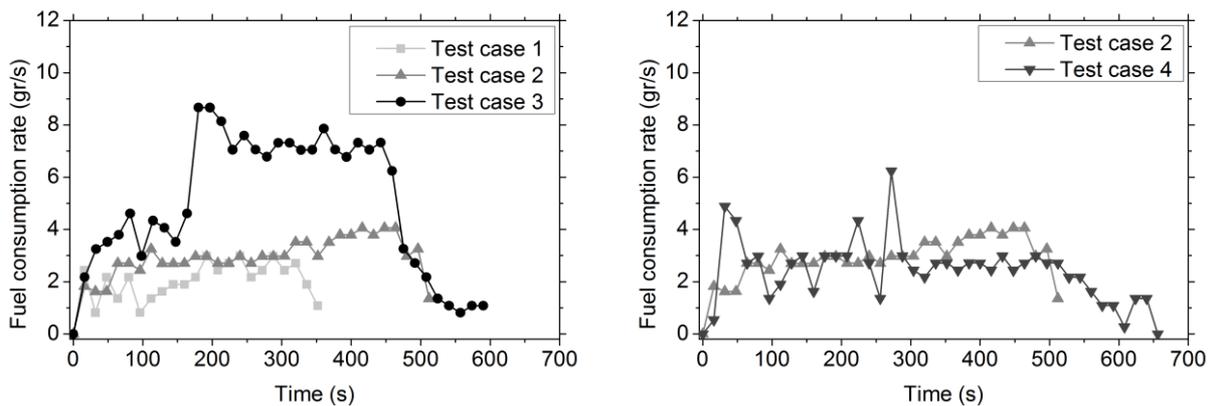


Figure 3. Measurements of instantaneous fuel mass consumption rate; effect of fire load (left) and opening factor (right).

4.2 EVF Gas Temperatures

The gas temperature evolution inside the compartment exhibits similar characteristics in all test cases; the three 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 (Figure 4). Average values of the gas temperature measured 300 mm, 400 mm and 500 mm above the floor of the fire compartment, at positions CB and CF (c.f. Figure 2), were used for the calculation of the temporal variation of the upper layer gas temperature shown in Figure 4. As expected, higher fire loads and increased opening size result in higher upper layer gas temperatures in the fire compartment.

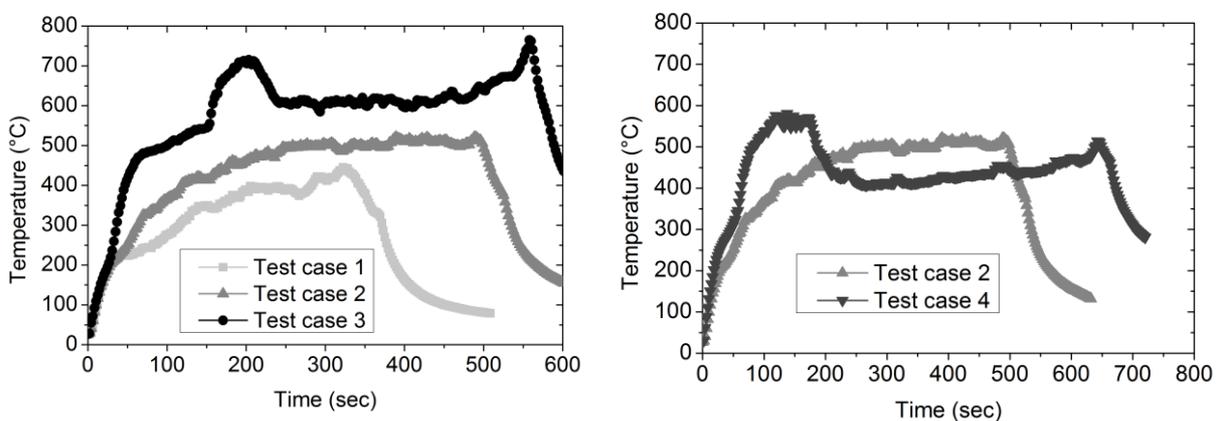


Figure 4. Temporal variation of upper layer gas temperature at the interior of the fire compartment; effect of fire load (left) and opening factor (right).

The vertical distribution of the gas temperature in the front side of the compartment, near the opening (location CF), is notably higher in test case 3, indicating that combustion still occurs further away from the fuel pan (Figure 5, left). The increased fuel load results in flames shifting to the rear of the compartment, creating a recirculating flow pattern inside the compartment, resulting in a larger EVF ejecting from the opening (Figure 5, left). In test case 4, decreasing the opening area results in elevated temperatures at the back side of the fire compartment (location CB), compared to test case 2; in addition, temperature variations along the height of the compartment are more modest in test case 4 (Figure 5, right). The opening area acts as an exhaust for the hot gases; in test case 4, the restricted outflow results in an increased residence time of the high temperature combustion products at the back of the compartment, that contribute to the observed high gas temperatures at position CB.

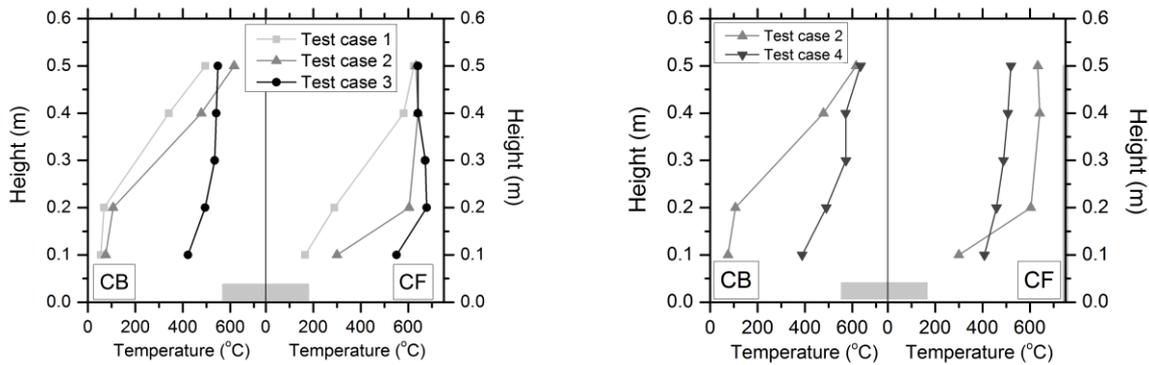


Figure 5. Vertical distribution of time-averaged gas temperature at the interior of the fire compartment; effect of fire load (left) and opening factor (right).

4.3 EVF Centreline Temperatures

Figure 6 illustrates the vertical distribution of the time-averaged gas temperatures at the EVF centerline; measurements are compared to results of the empirical correlations presented in Table 1, in an attempt to evaluate the applicability and effectiveness of each method. The thermocouple trees used at the exterior of the fire compartment, were located to the estimated centerline of the EVF. Initial calculations, employing the Eurocode 1⁶ methodology, indicated that EVF projection from the opening is expected to be 246 mm for test cases 1, 2, 3, and 592 mm for test case 4. The EVF centerline was assumed to be equal to $\frac{1}{2}$ of the overall projection distance, i.e. 123 mm (location TC1) for test cases 1, 2, 3 and 246 mm (location TC2) for test case 4 (c.f. Figure 2). During the testing period, these preliminary estimations were found to be close to the observed centerline of the flame¹⁹. Determination of the virtual height for correlation T2 is based on the assumption that EVF emerges from the upper half of the opening, which is assumed to be the fuel source of an axisymmetric fire plume¹⁴. Regarding the heat release rate values used in the various correlations, the total HRR inside the compartment ($Q_{ins,m}$) was used in correlation T1⁶, whereas the excess HRR due to the excess fuel burning outside the compartment (Q_{ex})^{8,14} was used in T2, T3 and T4 correlations^{1,10,14} (Eq. 5).

$$Q_{ex} = Q - Q_{ins,m} = Q - 1500D_v(H_v)^{1/2} \quad [5]$$

A comparison of EVF centerline temperature measurements to predictions obtained by using the correlations T1-T4 are shown in Figure 6. Under low fire load conditions (e.g. test case 1) correlations T2 and T3^{1,14} are found to over-predict experimental data, whereas correlation T4¹⁰ shows a remarkable agreement with measured values. In cases of increased fire load (e.g. test case 3) correlation T1⁶ and T4, considerably under-predict measured values, whereas correlations T2 and T3 over-predict the experimental data. The point heat source assumption¹⁴ employed in correlation T2,

results in good qualitative agreement with measured centerline temperatures in test cases 1, 2 and 4. Nevertheless, predictions of this correlation, originating from the experimental investigation of fire plumes (considered as upward hot currents) do not agree quantitatively with EVF centerline temperature, especially near the opening. Yokoi's methodology, correlation T3¹, over-predicts experimental data in test cases 1, 2 and 3 but appears to accurately estimate temperatures near the opening for all test cases. Correlation T4¹⁰ shows good qualitative and quantitative agreement in test cases 1, 2 and 4 but slightly under-predicts the measured values in test case 3. Generally, the observed discrepancies between experimental data and correlations may be attributed to the fact that the performed experiments resulted in continuous and consistent EVF, whereas literature reports suggest that the majority of correlations originate from temperature measurements in the fire plume region. Even though it has been demonstrated that the use of T1 correlation under-estimates experimental values, correlations T2¹⁴, T3¹ and T4¹⁰ may be safely used, although they exhibit reduced accuracy in positions near the top of the opening.

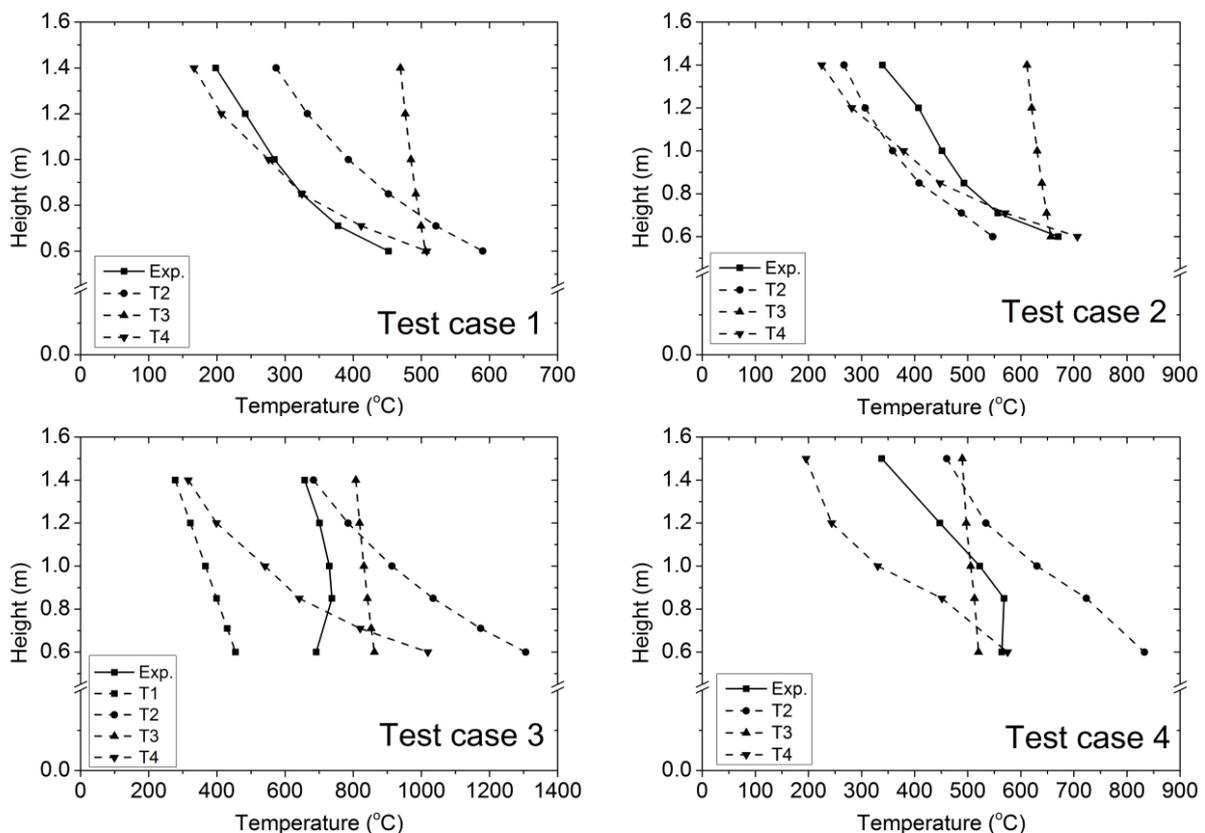


Figure 6. Vertical distribution of measured and predicted time-averaged Centreline EVF temperatures; effect of fire load (left) and opening factor (right).

4.4 Temperatures on the Exposed Façade Surface

Vertical distribution of the time-averaged wall temperature at the centreline (position F) and $\frac{1}{4}$ of the width (position FM) of the façade (c.f. Figure 2) are illustrated in Figure 7. Façade surface temperatures are found to generally increase with increasing height, until they reach their maximum value, where they start to decrease again. As expected, wall temperatures are directly correlated to EVF centreline temperatures (c.f. Figure 6); the higher the latter the more increased the former. Surface temperatures at the façade centreline (position F) directly exposed to EVF, exhibit higher values compared to values at the $\frac{1}{4}$ of the façade width (position FM).

In test case 3, which is characterised by relatively larger excess heat release rate values resulting in a longer EVF plume, higher façade surface temperatures are recorded. The temporal evolution of façade surface temperatures at two characteristic heights from the ground, 0.6 m (Figure 8) and 1.2 m (Figure

9), indicate that the decreased opening area of test case 4 results in elevated temperatures at the façade's centreline, compared to test case 2. This is not the case for position FM, where wall temperatures in test case 2 exhibit higher values during the period of fully developed fire phase. The temperature distribution at the exposed façade surface, recorded by a thermal camera at the end of test cases 2 and 4 (Figure 10), illustrates the latter statement.

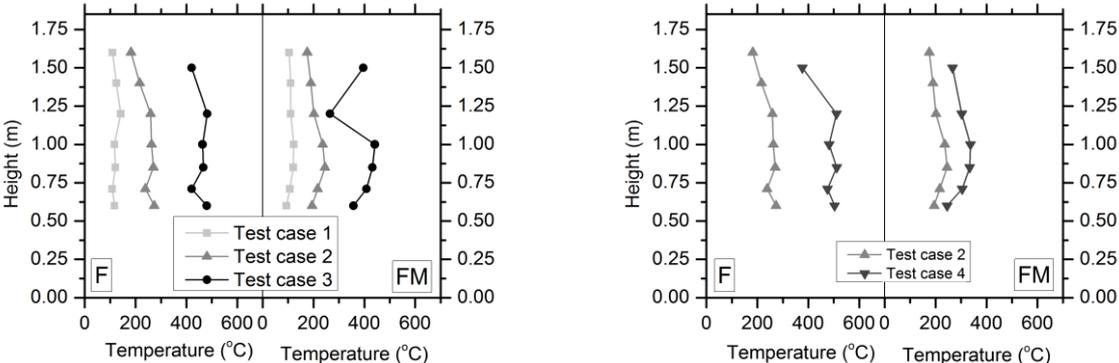


Figure 7. Vertical distribution of time-averaged wall temperature at the façade surface exposed to EVF; effect of fire load (left) and opening factor (right).

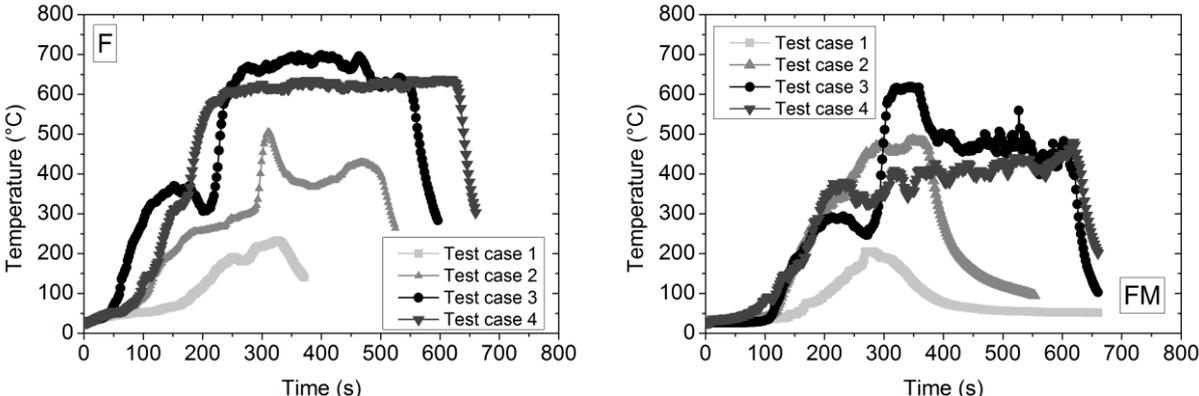


Figure 8. Temporal variation of wall temperatures at the exposed façade surface, at a height of 0.6 m.

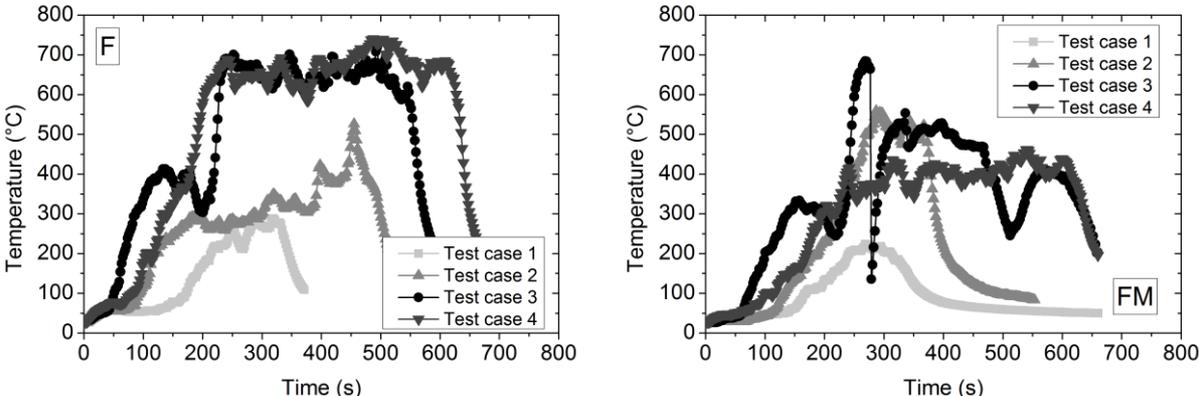


Figure 9. Temporal variation of wall temperatures at the exposed façade surface, at a height of 1.2 m.

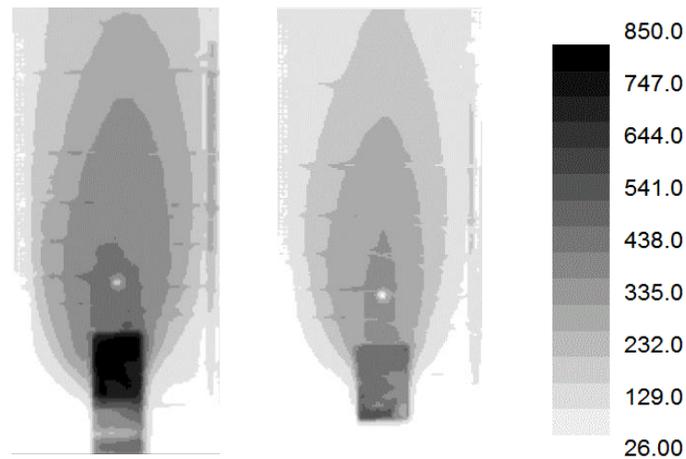


Figure 10. Temperature profiles of the exposed façade surface recorded by thermal camera at the end of test case 2 (left) and 4 (right).

4.5 Heat Flux on the Exposed Façade Surface

The temporal evolution of the measured and calculated heat flux values at the exposed surface are illustrated in Figure 11; the latter values are estimated using the methodologies presented in Section 2.2 and Table 2. A typical behaviour of an under-ventilated compartment fire can be observed^{15, 21} which is characterized by 3 distinct phases that appear in succession²². Initially, combustion is constrained in the interior of the fire compartment (“internal flaming”) and in the vicinity of the fuel pan an advection stream is created. Gradually, the flame front moves away from the fuel pan, expanding radially and horizontally towards the opening. In that phase, external flame jets and quick flashes appear at the exterior of the fire compartment, signifying the beginning of the “intermittent flame ejection” stage. As time passes, “Consistent External Flaming” (CEF) is observed due to the sustained external combustion of unburnt volatiles, during the quasi-steady phase of fully developed fire. Throughout the latter phase, EVF consistently covers the region above the opening resulting in higher values of heat flux in the façade surface. CEF period, heat flux values measured at characteristics instances and predicted values employing each methodology are summarised in Table 4 for all test cases. It appears that the most important parameter influencing the results is the effect of fuel properties on the calculation of extinction coefficient, Method HF3.

Table 4: Measured and predicted heat fluxes at 0.11 m above the opening soffit.

	CEF period (s)	212 - 372	108 - 525	55 - 595	124 - 659
	Heat Flux (kW/m²)	Test case 1	Test case 2	Test case 3	Test case 4
Measured	<i>t</i> = 100 s	1.41	8.51	25.36	8.84
	<i>t</i> = 300 s	21.23	53.79	64.37	47.08
	<i>t</i> = 500 s	-	14.37	63.75	51.91
	<i>t</i> = 600 s	-	-	-	50.41
	Maximum value	24.32	53.79	89.33	64.48
	Average value	12.88	23.67	48.63	44.68
Predictions	Method HF1	8.38	15.92	28.99	17.43
	Method HF2	7.46	14.32	26.97	16.43
	Method HF3	17.40	39.74	81.03	40.44
	Method HF4	14.74	20.80	28.30	19.85
	Method HF5	3.60	7.30	13.90	6.42

The impact of flame shape on the prediction of heat flux was investigated through comparison of Methods HF1 and HF2. Method HF1 is used as a base case; its predictions under-predicted the experimental data. Predictions of method HF2 outperformed method HF1; however the improvement on accuracy cannot be considered significant. When method HF3 is implemented, which takes into account the specific fuel properties for the estimation of the extinction coefficient, predictions err on the safe side with the exception of test case 4. Less conservative calculations were derived when method HF4 was utilized, where a constant value of convective coefficient was employed, as proposed in Eurocode 1 for external fires. When a more rigorous methodology was used to estimate the convective coefficient, (method HF5), results were not significantly improved; this can be attributed to the fact that the guidelines for the application of Eq. (3) on façades exposed to EVF are rather obscure.

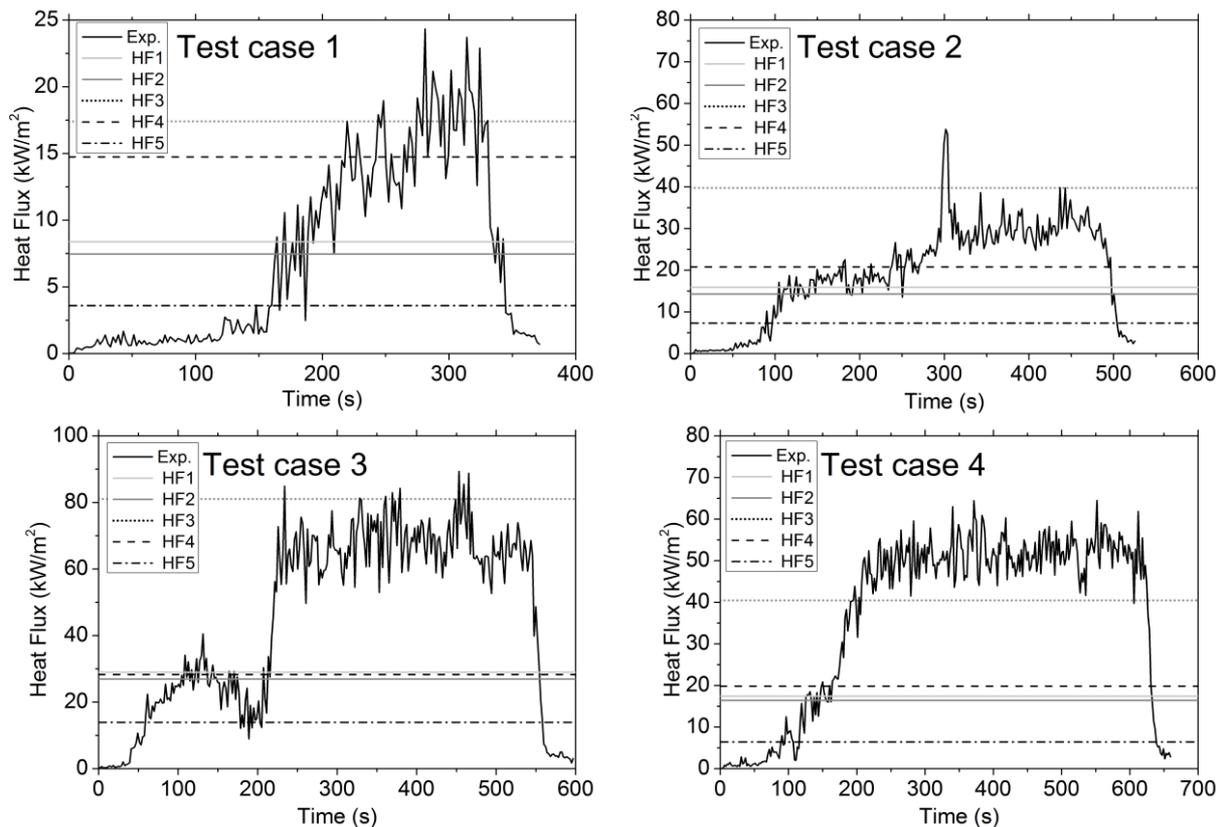


Figure 11. Temporal evolution of measured and predicted heat flux values on the exposed façade surface.

5. CONCLUSIONS

A series of medium-scale fire compartment experiments was performed, utilizing a $\frac{1}{4}$ scale model of the ISO 9705 compartment, equipped with an extended façade. An “expendable” fuel source (n-hexane liquid pool fire) was utilized to effectively simulate realistic building fire conditions. A range of realistic fire scenarios, relevant to building fires, was developed. A series of experiments were conducted by modifying the total fuel load (test cases 1, 2 and 3) and the opening dimensions (test case 4); the fire load used in test case 4 was identical to the fire load used in test case 2. Test cases 2, 3 and 4 corresponded to under-ventilated fire conditions; in test case 1, a slightly over-ventilated fire was developed, due to the low fire load used. Experimental results suggested that the flame geometry and EVF duration are mainly affected by the opening dimensions, whereas the fuel load has a significant impact on the heat flux to the façade.

This work also focused on the evaluation of available fire engineering design correlations aiming to estimate EVF characteristics and its effects on an adjacent façade, using the obtained experimental data. As far as the EVF centreline temperature calculation is concerned, it has been demonstrated that the use of the T1 correlation under-estimates experimental values. Correlations T2¹⁴, T3¹ and T4¹⁰ may be safely used, although they exhibit reduced accuracy in positions near the top of the opening; however, the calculated values err on the safe side. Observed discrepancies may be attributed to the fact that empirical correlations used for predicting the geometry and centerline temperature of the EVF were derived from experiments mainly involving cellulosic fuel load^{1,13} or constant HRR burners^{23,24}. Implementation of method HF3 to estimate the heat flux on the façade surface exposed to EVF, taking into account fuel properties for the estimation of the extinction coefficient, was found to provide conservative results.

It is widely accepted that the suitability of a simplified fire safety calculation methodology is determined for its intended application by verification through accurate experimental measurements; only a method that is both versatile and practice oriented, yielding sufficiently accurate results, may prove appropriate for wider use. Acknowledging these facts and taking into consideration that simplified methodologies, as the ones employed in this work, must produce conservative design values, there is a great need for design guidelines that provide explicit recommendations on how to use them. Even if more sophisticated models are available, a compromise is often necessary between accuracy, cost and time. Knowledge of the errors and limitations of fire engineering correlations is necessary if an analytical approach is used as an alternative to performance-based methodologies.

The obtained extensive set of experimental data, pertinent to both the interior and exterior of the fire compartment, can be used to validate CFD models or evaluate the accuracy of other available fire design correlations. Using medium- and full-scale compartment-façade fire configurations, a range of realistic fire scenarios will be investigated in the future, by varying a number of significant operational parameters such as ventilation conditions, fire load, opening dimensions and the relative height of the fuel package. Emphasis will be given in evaluating the accuracy of available semi-empirical correlations and methodologies used for the calculation of EVF envelope, centreline temperatures and heat flux on the façade surface.

6. ACKNOWLEDGEMENTS

This work has been financially supported by the “Fire-FACTS” project in the frame of the ARISTEIA action (operational programme "Education and Lifelong Learning") that is co-financed by Greece and the E.U. and by the E.C. in the frame of the FP7 project "ELISSA: Energy Efficient Lightweight-Sustainable-Safe-Steel Construction" (EeB.NMP.2013-1, Grant No. 609086). The assistance of Dipl. Eng. Konstantinos Chotzoglou in the development, installation and testing phases of this work is gratefully acknowledged.

7. REFERENCES

- ¹ Thomas, I.R., Moinuddin, K.A. and Bennetts, I.D. (2007) ‘The effect of quantity and location on small enclosure fires’, *Journal of Fire Protection Engineering*, vol. 17, p85-p102.
- ² White, N. and Delichatsios, M. (2014) ‘Fire Hazards of exterior wall assemblies containing combustible components’, Final Report, Fire Protection Research Foundation.
- ³ Yokoi, S. (1960) ‘Study on the prevention of fire spread caused by hot upward current’, Building Research Institute, Report No. 34, Tokyo, Japan.

- ⁴ Oleszkiewicz, I. (1989) 'Heat transfer from a window fire plume to a building façade', Reprinted from "Collected papers in heat transfer", HTD-Vol. 123, Editors: Marner W.J., Chen T.C., Faghri M., Peterson G.P., Kuehn T.H., Pate M.B., Mahajan R.L. and Lavine A.S., Book No. H00526.
- ⁵ Tang, F., Hu, L.H., Delichatsios, M.A., Lu, K.H. and Zhu, W. (2012) 'Experimental study on flame height and temperature profile of buoyant window spill plume from an under-ventilated compartment fire', *International Journal of Heat and Mass Transfer*, vol. 55, p93-p101.
- ⁶ Eurocode 1 (EN 1991-1-2) (2002) 'Actions on structures, Part 1-2 – General Actions – Actions on Structures Exposed to Fire', Brussels.
- ⁷ Klopovic, S. and Turan, O.F. (2001) 'A comprehensive study of externally venting flames, Part I: Experimental plume characteristics for through-draft and no through-draft ventilation conditions and repeatability', *Fire Safety Journal*, vol. 36, p99-p133.
- ⁸ Klopovic, S. and Turan, O.F. (2001) 'A comprehensive study of externally venting flames, Part II: Plume envelope and center-line temperature comparisons, secondary fires, wind effects and smoke management system', *Fire Safety Journal*, vol. 36, p135-p172.
- ⁹ Empis, C.A. (2010) 'Analysis of the compartment fire parameters influencing the heat flux incident on the structural façade', PhD University of Edinburg.
- ¹⁰ Himoto, K., Tsuchihashi, T., Tanaka, Y. and Tanaka, T. (2009) 'Modeling thermal behaviors of window flames ejected from a fire compartment', *Fire Safety Journal*, vol. 44, p230-p240.
- ¹¹ Asimakopoulou, E., Kolaitis, D. and Founti, M. (2013) 'Comparative assessment of CFD tools and the Eurocode methodology in describing Externally Venting Flames', 1st International Seminar for Fire Safety of Façades, 14-15 November, Paris, France.
- ¹² Heskestad, G. (1983) 'Virtual origins of fire plumes', *Fire Safety Journal*, vol. 5, p109-p114.
- ¹³ Law, M. (1978) 'Fire safety of external building elements – The design approach', *AISC Engineering Journal*, Second Quarter.
- ¹⁴ Beyler, C.L. (1986) 'Fire Plumes and Ceiling Jets', *Fire Safety Journal*, vol. 11, p53-p75.
- ¹⁵ DiNenno, P.J., Drysdale, D., Beyler, C.L., Walton, W.D., Custer, R.L.P., Hall, J.R. and Watts, J.M. (2002) 'SFPE Handbook of fire protection engineering', Third Edition, SFPE, Quincy, Massachusetts.
- ¹⁶ Quintiere, J.G. (2006) 'Fundamentals of fire phenomena', John Wiley.
- ¹⁷ Delichatsios, M., Lee, Y., Tofilo, P. (2009) 'A new correlation for gas temperature inside a burning enclosure', *Fire Safety Journal*, vol. 44, p1003-p1009.
- ¹⁸ ISO 9705, International Organization for Standardization: Geneva, Switzerland, ISO 9705, "Fire Tests: Full-Scale Room Test for Surface Products", First Edition, 1993.
- ¹⁹ Asimakopoulou, E., Kolaitis, D. And Founti, M. (2015) 'Evaluation of fire engineering design correlations for Externally venting Flames using a medium-scale compartment-façade fire experiment', 9th Mediterranean Combustion Symposium, 7-11 June, Rhodes, Greece.
- ²⁰ Korhonen, T. and Hietaniemi, J. (2005) 'Fire safety of wooden façades in residential suburb multi-storey buildings', VTT Working Papers 32.
- ²¹ Drysdale, D. (2011) 'An Introduction in Fire Dynamics', John Wiley, New York.
- ²² Gottuk, D.T., Roby, R.J. and Beyler, C.L. (1992) 'A study of CO and smoke yields from compartment fires with external burning', *Proceedings of Combustion Institute*, vol. 24, p1729-p1735.
- ²³ Hu, L., Lu, K., Delichatsios M., He L. and Tang F. (2012) 'An experimental investigation and statistical characterization of intermittent flame ejecting behaviour of enclosure fires with an opening', *Combustion and Flame*, vol. 159, p1178-p1184.
- ²⁴ Lee, Y., Delichatsios, M.A. and Silcock G.W.H. (2008) 'Heat flux distribution and flame shapes on the inert façade', *Fire Safety Science*, vol. 9, p193-p204.