An experimental and numerical investigation of externally venting flames developing in an under-ventilated fire compartment-façade configuration

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Abstract
Externally Venting Flames (EVF) may significantly increase the risk of fire spreading. The main scope of this study is to investigate the fundamental physical phenomena governing EVF development and to assess the ability of currently available CFD tools to adequately describe EVF characteristics. In this context, a series of medium scale compartment-façade configuration fire experiments are performed. Experimental results suggest that the fuel load has a significant impact on the heat flux to the façade. The Fire Dynamics Simulator (FDS) CFD tool is used for the numerical simulation of the turbulent, multi-component and reactive flow-field developing in the experimental apparatus.

1. Introduction

Externally Venting Flames (EVF) may emerge in a fully developed under-ventilated compartment fire, thus significantly increasing the risk of fire spreading to adjacent floors or buildings. EVF related risks are constantly growing due to the ever-increasing trend of using combustible materials (e.g. insulation) in facades to enhance building energy efficiency. Despite this fact, the majority of currently available fire safety codes are lacking specific methodologies to evaluate the risks associated with EVF. Historically, fire protection systems in buildings have been commonly regulated using prescriptive codes, however, there is a growing trend towards employing performance-based codes; implementation of the latter requires the use of advanced simulation tools such as Computational Fluid Dynamics (CFD) software. CFD tools may provide significant assistance to the fire safety engineering analysis of EVF by offering the opportunity to obtain an in-depth knowledge of the spatial and temporal distribution of important physical parameters, such as velocity, gas temperature, wall temperature etc.

The main scope of this study is to investigate the fundamental physical phenomena governing EVF development and to assess the ability of currently available CFD tools to adequately describe EVF characteristics. In this context, a series of medium scale fire compartment experiments is performed, utilizing a ¼ scale model of the ISO 9705 room, equipped with an extended façade. An "expendable" fuel source (n-hexane liquid pool fire) is utilized to effectively simulate realistic building fire conditions. An extensive sensor network is used to obtain a detailed description of the developing EVF. The temporal evolution of various physical parameters, such as fuel mass loss, gas and wall surface temperatures and façade heat flux, is recorded. A parametric study is also performed by varying fire load, which is known to significantly affect EVF behavior. The dynamic nature of EVF is captured and a typical behavior of EVF developing in an under-ventilated compartment fire is observed. Experimental results suggest that the fuel load has a significant impact on the heat flux to the façade.

The Fire Dynamics Simulator (FDS) CFD tool, which utilizes the Large Eddy Simulation approach, is used for the numerical simulation of the turbulent, multi-component and reactive flow-field developing in the medium scale compartment-façade configuration. Numerical results of the temporal evolution of gas velocity, gas and wall temperatures and heat flux on the façade wall are obtained for both the interior and the exterior of the configuration. Predictions are compared to respective experimental data; good qualitative, and occasionally quantitative, agreement is observed in all the considered test cases.

2. Medium-scale compartment-façade configuration

A series of fire experiments was conducted in a medium-scale compartment-façade fire apparatus. The compartment was a ¼ scale model of an ISO 9705 compartment [1]. 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, depicting the locations of the measuring devices, is shown in Figure 1.

3. 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 along the front and rear corner 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

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Proceedings of the European Combustion Meeting 2015

compartment. Emphasis was given to the characterization of the thermal 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 1). 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 [2].

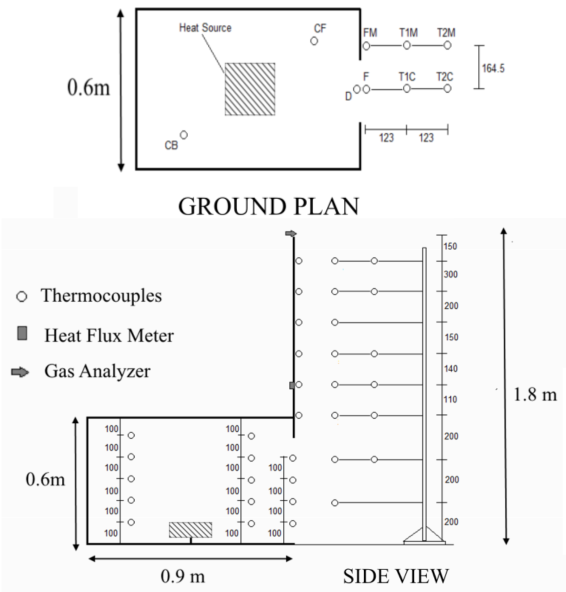

Figure 1: General layout of the medium scale compartment-façade configuration.

4. Parametric Study

The fire load may have a significant impact on the risk of fire spread due to EVF [3]. Thus a parametric study was performed, by varying the total fire load in the compartment, Test Cases 1 and 2.

Gaseous burners are commonly used in relevant fire compartment experiments [4, 5], 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 at 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 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) [6], average heat release rate at the interior of the fire compartment ($Q_{ins,m}$) and excess heat release rate (Q_{ex}) [5], for the 2 Test Cases examined, is given in Table 1. Both Test Cases corresponded to under-ventilated fire conditions.

Table 1: Summary of main operational parameters for the examined test cases.

	Test Cases	
	1	**2**
$\boldsymbol{H_v}$ **(m)**	0.5	0.5
$\boldsymbol{W_v}$ **(m)**	0.2	0.2
$\boldsymbol{T_\infty}$ **(°C)**	26.7	26.5
$\boldsymbol{RH_\infty}$ **(%)**	42.0	47.0
$\boldsymbol{t_{dur}}$ **(s)**	525	595
$\boldsymbol{m_f}$ **(kg)**	1.539	6.078
GER **(-)**	1.224	2.159
$\boldsymbol{Q_{ins,m}}$ **(kW)**	106.5	106.5
$\boldsymbol{Q_{ex}}$ **(kW)**	25.5	126.5

5. Numerical Simulation

The Fire Dynamics Simulator (FDS) code, version 6.1.2, was used to simulate the turbulent, multi-component and reactive flow-field developing in the interior and exterior of the compartment-façade configuration. The FDS code is a CFD tool capable of studying fundamental fire dynamics and combustion, aimed at solving practical fire problems in fire protection engineering [7]. The FDS code solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flows; with an emphasis on smoke production and heat transfer from fires. The core algorithm is an explicit predictor-corrector scheme that is second order accurate in space and time. Turbulence is treated by using the Large Eddy Simulation (LES) approach. The subgrid-scale turbulence is simulated using the Deardorff model, utilizing a Deardorff constant value of 0.1. The numerical time-step is continuously adjusted in order to satisfy the CFL criterion. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences and the solution is updated in time on a three-dimensional, Cartesian grid. Thermal radiation is simulated using the finite volume methodology on the fluid flow grid.

5.1 Simulation Details

FDS results are known to significantly depend on the size of the numerical grid due to LES approximation [7]. In the general context of compartment fire simulations, the quality of the utilized grid resolution is commonly assessed using the non-dimensional $D^*/\delta x$ ratio, where D^* is a characteristic fire diameter and δx

corresponds to the nominal size of the grid cell. The $D^*/\delta x$ ratio corresponds to the number of computational cells spanning D^* and is representative of the adequacy of the grid resolution. If the value of the $D^*/\delta x$ ratio is sufficiently large, the fire can be considered well resolved. Several studies have shown that values of 10 or more are required to adequately resolve most fires and obtain reliable flame temperatures [8]. In the current study, aiming to fulfil the $D^*/\delta x \geq 10$ criterion and, at the same time, reduce the required computational cost, a 0.025 m cell size was selected ($D^*/\delta x$=10).

The total number of computational cells is 133.120 and at the beginning of the numerical simulation, the entire computational domain (both indoors and outdoors) is assumed to be still (zero velocity), exhibiting a temperature of 20^{o}C. The total simulation time is selected to be equal to 525 s and 595 s for test Case 1 and 2, respectively. Open boundaries are imposed at all boundaries external to the enclosure and wall boundary conditions are used at walls, ceiling and floor. In order to simulate the "realistic" fire condition of each Test Case, a variable mass loss rate according to available experimental data of fuel consumption rate has been used, Figure 2. The FDS code simulates combustion phenomena using a "mixture-fraction" model, assuming infinitely fast mixing of fuel and oxygen (fuel and oxygen cannot co-exist and they react at any temperature). The soot yield, which represents the fraction of n-hexane fuel mass converted to smoke particulates, is set equal to 3.5 %, according to available measurements [5]. Regarding flame extinction in FDS, the only parameters that can be controlled are the Limiting Oxygen Index (LOI) and the critical flame temperature; in the current study LOI value was set 0.15 mol/mol.

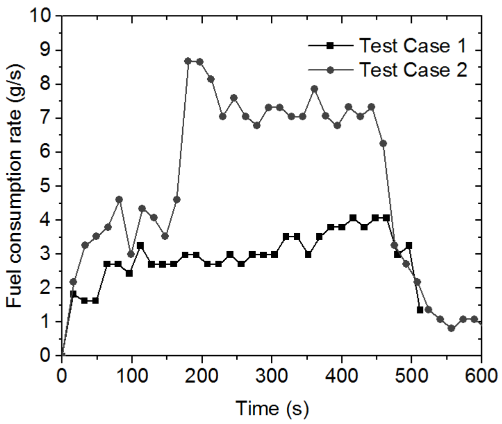

Figure 2: Measurements of instantaneous fuel consumption rate for Test Cases 1 and 2.

6. Results and Discussion

6.1 Fire compartment gas temperatures

The vertical distribution of the time-averaged gas temperature at the front (location CF) and the rear of the compartment (location CB) for Test Cases 1 and 2 are presented in Figure 3 and 4, respectively. Higher fire loads result in higher gas temperatures and in both cases the vertical distribution of the gas temperature is notably high indicating that combustion still occurs further away from the fuel pan near the opening.

Generally, predictions of the time-averaged gas temperature at the interior of the fire compartment show good levels of qualitative agreement with measured values. In Test Case 1, predictions accurately depict the gas temperature vertical distribution whereas in Test Case 2, FDS tends to under-predict the measured values. This behaviour may be attributed to the difficulty of the FDS code to accurately predict the presence of the fire plume in the interior of the fire compartment in under-ventilated conditions [9], pertaining to both the examined Test Cases. One of the possible ways to control the extinction of fire in the interior of the fire compartment is to manually modify the LOI in order to prevent increased burning near the opening. As already mentioned, in FDS, the combustion model assumes that fuel and oxygen burn instantaneously when mixed. This assumption may not be appropriate for incomplete combustion that commonly characterizes under-ventilated compartment fires.

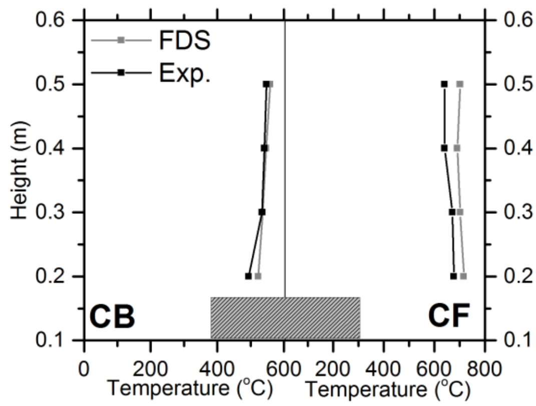

Figure 3: Vertical distribution of time-averaged gas temperature at the interior of the fire compartment (Test Case 1).

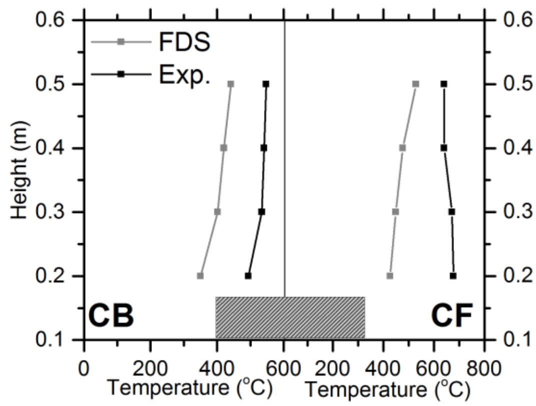

Figure 4: Vertical distribution of time-averaged gas temperature at the interior of the fire compartment (Test Case 2).

6.2 EVF centerline temperatures

Figures 5 and 6 illustrate the temporal evolution of the gas mixture temperatures at the EVF centerline at a height of 600 mm, 1000 mm and 1500 mm heights;

experimental measurements (Exp.) are compared to CFD predictions (FDS).

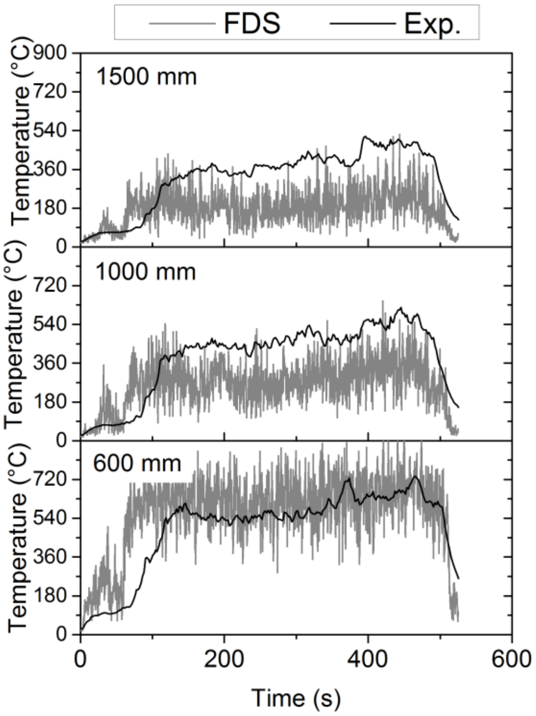

Figure 5: Temperature histories at a height of 600 mm, 1000 mm and 1500, 123 mm (location TC1) from the façade (Test Case 1).

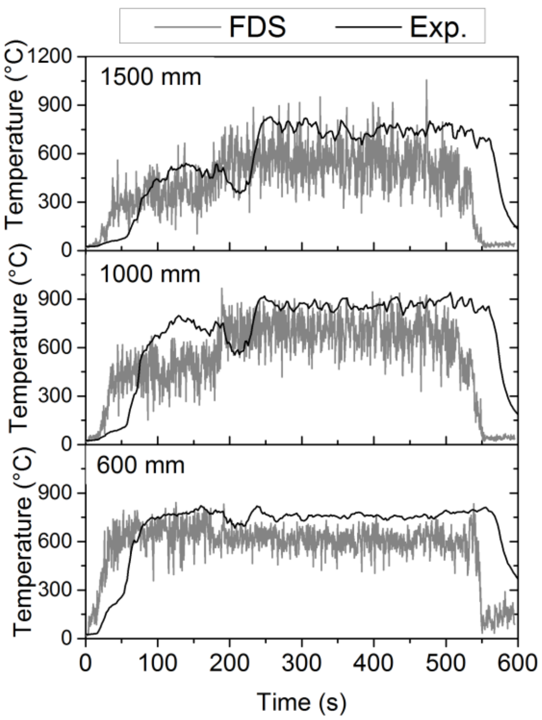

Figure 6: Temperature histories at heights of 600 mm, 1000 mm and 1500 mm, 123 mm (location TC1) from the façade (Test Case 2).

Initial calculations, employing the Eurocode 1 [10] methodology, indicated that EVF projection from the opening is expected to be 246 mm for both Test Cases. The EVF centreline was assumed to be equal to ½ of the overall projection distance, i.e. 123 mm (location TC1) (c.f. Figure 1). During the testing period, these preliminary estimations were found to be close to the observed centreline of the flame [2].The effect of fire load on the EVF temperatures is evident; as expected, higher fire load results to a more intense EVF plume exhibiting higher temperature gradients. In general, good quantitative agreement is observed, especially at lower heights. FDS generally under-predicts experimental values; only at a height of 600 mm there is an overall over-prediction, (Test Case 1).

6.3 Exposed façade surface: heat flux and temperature

The temporal evolution of the measured and predicted heat flux values at the façade centerline 710 mm height from the ground are illustrated in Figure 7 for Test Cases 1 and 2. A typical behavior of an under-ventilated compartment fire can be observed [6]. Initially, combustion is constrained in the interior of the fire compartment 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.

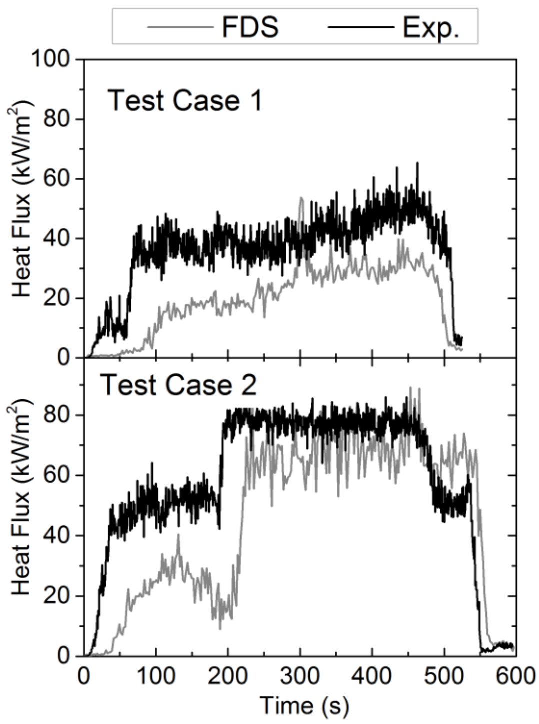

Figure 7: Temporal evolution of heat flux to the façade wall, at a height of 710 mm, for Test Cases 1 and 2.

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. Measured heat flux values are generally lower than CFD predictions, in accordance to the previously presented EVF centerline temperatures at 600 mm height from the ground for Test Case 1 (c.f. Figures 5). As expected, the façade wall is directly exposed to a more intense EVF plume in Test Case 2, thus exhibiting higher heat flux gradients. CFD predictions in Test Case 2 indicate better levels of agreement with experimental data. CEF is observed after the first 108 s and 55 s for Test Cases 1 and 2 respectively (c.f. Figure 7); numerical predictions are capable of accurately predicting the start time of the CEF period.

Experimental, recorded by a thermal camera at the end of Test Case 1, and predicted temperature distribution at the exposed façade surface is illustrated in Figure 8. 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 5 and 6), exhibiting a qualitatively similar vertical profile. Surface temperatures at the façade centreline directly exposed to EVF, exhibit higher values compared to values in off-centre positions. FDS generally under-predicts experimental values and only at lower heights, near the opening, an over-prediction can be observed.

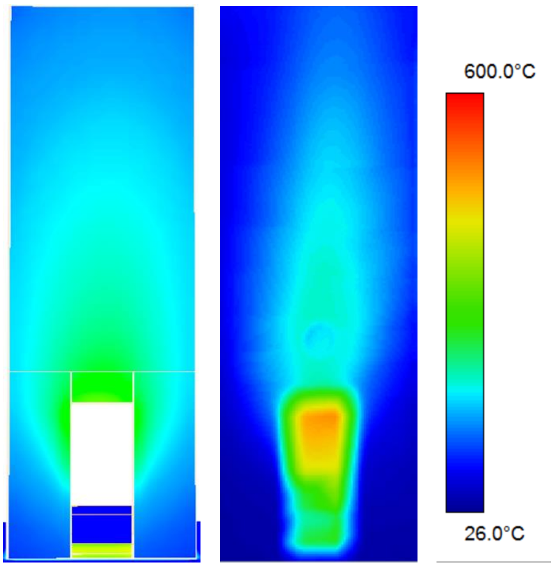

Figure 8: Predictions (left) and experimental values (right) of temperature profiles of the exposed façade surface at the end of Test Case 1.

6.4 Gas Velocity

Predictions of the gas phase velocity along with the resulting EVF envelope at the beginning and the end of Test Cases 1 and 2, are depicted in Figures 9 and 10, respectively. Initially, the fire plume originating from the fuel pan at the centre of the fire compartment, moves upward by free convection and impinges on the ceiling; thereby changing its flow direction. The flow then starts to spread out horizontally and diffuses toward the opening, where it reacts with ambient air, resulting in EVF. Two large counter-rotating vortices are continuously formed at the interior of the fire compartment (c.f. Figure 9 and 10), creating a recirculation zone that further forces the formed EVF towards the exterior of the fire compartment. As a result, the flame front is mainly situated near the opening and an EVF is established at the exterior of the fire compartment.

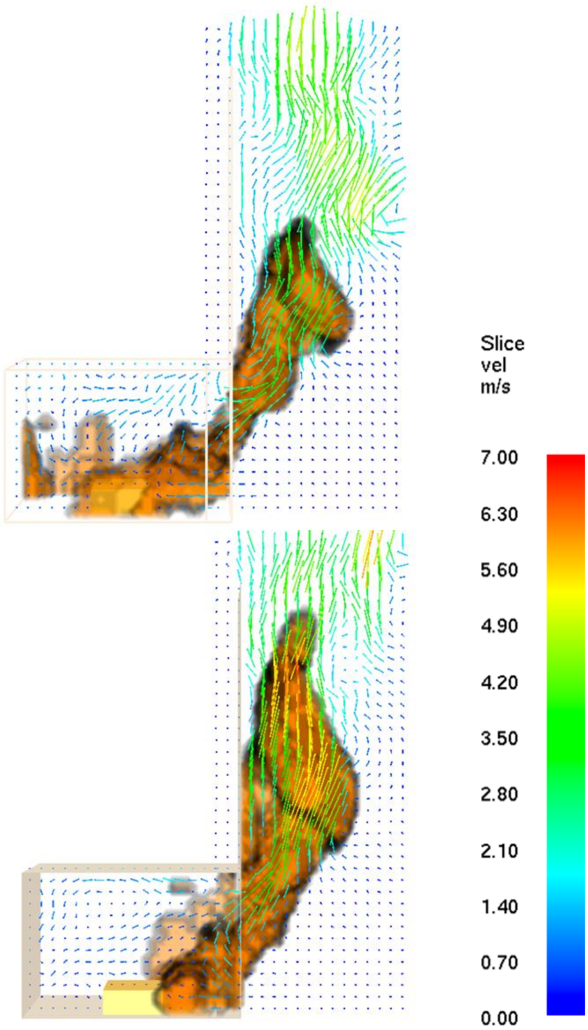

Figure 9: Predictions of velocity vectors and flame envelope 60 s after fire initiation, for Test Case 1 (top) and 2 (bottom).

The effect of fire load on the predicted EVF plume shape and velocity field is evident. In Test Case 2, the larger portion of combustion takes place outside the fire compartment (c.f. Table 1), thus resulting in a more intensified EVF plume that extends upwards from the opening. Air entrainment pushes EVF upward, forming a characteristic "neck" at the top of which, large eddy structures are formed [5]. In the EVF zone, velocity is increased with height as air entrainment effects become more intense at the plume region.

Near the end time of each Test Case the gas dynamics inside the fire compartment change (c.f. Figure 10). When the fire starts decaying, the upper layer begins to cool and a stronger flow of air enters the fire compartment through the lower part of the opening. As a result, the flame front moves back towards the interior of the fire compartment, resulting in a gradually decreased EVF volume.

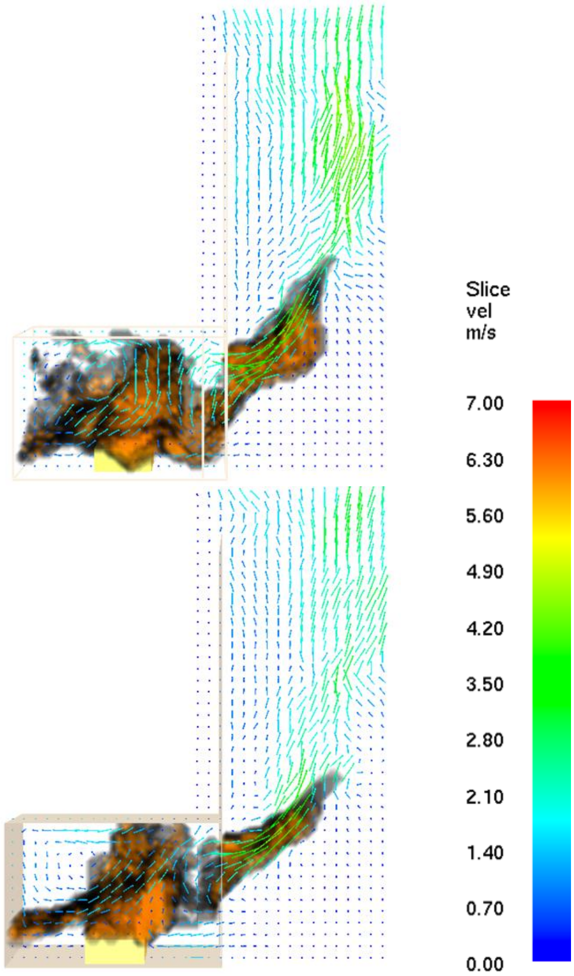

Figure 10: Predictions of velocity vectors and flame envelope for Test Case 1 (top), 525 s after fire initiation, and 2 (bottom), 595 s after fire initiation.

7. Conclusions

A series of medium-scale fire compartment experiments was performed, utilizing a ¼ 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.

The dynamic nature of EVF requires the use of advanced modeling methodologies, capable of describing the relevant physical phenomena in sufficient detail; the commonly used prescriptive methodologies are based on a phenomenological approach that exhibits certain limitations, especially when unusual structures are considered. CFD tools may provide significant assistance to the fire safety engineering analysis of EVF, by offering the opportunity to obtain an in-depth view of the spatial and temporal distribution of important physical parameters such as velocity, gas temperatures, wall temperatures, heat flux etc. The ability of currently available CFD tools to adequately describe EVF is assessed, using in-house experimental measurements of a medium scale compartment-façade configuration exposed to realistic fire conditions. The obtained predictions are compared to available experimental data. In the interior of the fire compartment, good qualitative and occasionally quantitative agreement is observed for the gas temperatures. By adjusting the LOI parameter and the combustion model, more accurate results may be achieved. The performance of the CFD tool in predicting EVF gas temperatures and heat flux to the adjacent façade is improved in higher fire loads.

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, opening dimensions and relative height of the fuel package.

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.

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