SMOKE CONCENTRATIONS INSIDE AND OUTSIDE OF CORRIDOR-LIKE ENCLOSURE FIRES

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Abstract
This work compares smoke measurements inside and outside of corridor-like enclosures for under ventilated fires to determine the smoke concentrations inside and outside the enclosure having also flames emerging outside the opening. Thirty five experiments were performed in a three metre long corridor-like compartment (of cross section 0.5 times 0.5 metres) having a gaseous burner located near the closed end. Smoke concentrations were measured in two locations inside the enclosure and also in the exhaust duct of a hood collecting the fire gases from the testing rig. In addition, the flow pattern was examined by bidirectional probes, temperature measurements and oxygen concentrations in the upper and lower layer inside the enclosure. It was found that smoke concentrations decreased in the exhaust duct after flames emerged from the opening relative to levels measured before external burning. At the same time, smoke concentrations inside increased compared to fire without flames outside. This difference in concentrations is due to the reversion of flow pattern inside the enclosure before and after the flames moved towards the opening as manifested by the bidirectional probe velocity and oxygen concentrations measurements. Namely, the flow pattern changed behind the travelling flame front, i.e. hot gases in the upper layer were travelling backwards towards the closed end of the corridor thus contributing to smoke accumulation inside the enclosure whereas they were travelling the opposite way ahead of the flame front.

Introduction
Production of smoke and carbon monoxide is the major contributor to fatality in compartment fires and as a result has attracted great research attention over the last decades. Of particular interest in this work is smoke production in enclosures. Smoke production is often investigated by means of light extinction measurements. Only few studies conducted recently [1-3] contained data on smoke measurements inside compartments. However, there is lack of comprehensive comparisons of the smoke measurements inside and outside the compartment.

Studies [4-6] have shown that external burning reduces the amount of carbon monoxide production downstream of a compartment, owing to more complete combustion. Because it has been shown in [7,8] that smoke and carbon monoxide production for underventilated fires may be governed by similar factors, one may assume that external burning may also reduces the amount of smoke production downstream of a compartment. These phenomena will be closely examined in this work.

The objective of this work is to examine the effects of external burning on smoke production in underventilated fires. In contrast to previous studies, where only smoke outside the compartment was measured, smoke production inside and outside a corridor-like enclosure was recorded simultaneously in this work. In addition to smoke production, measurements also include total heat release rates, gas temperatures, species concentrations and velocity inside the enclosure respectively by means of oxygen calorimetry, thermocouples, gas analysers and bi-directional probes. In order to investigate the effects of global equivalence ratio *(GER)* on smoke production, thirty-five tests were conducted with a range of *HRRs* and opening sizes.

The paper is organised in the following way. Firstly, experimental setup and instrumentation are described, with detailed information about uncertainty of the measurements. Results and discussions are presented next, followed by conclusions.

Experimental set-up

Experiments were performed in a corridor-like enclosure, which was 3m x 0.5m x 0.5m. The whole enclosure was constructed from cubic boxes connected together, as illustrated in Fig. 1. The amount of available air for combustion inside was varied by using different opening sizes in the front panel. Openings dimensions were (widths and heights, respectively): 7.5cm x 20 cm, 7.5cm x 30 cm 10cm x 25cm, 20cm x 20cm and 25cm x 10cm. Propane gas was supplied from a rectangular (10 x 20cm) sandbox burner controlled by a mass flow controller. The sandbox burner was located in the middle of the last box (Box F) at the opposite of the opening..

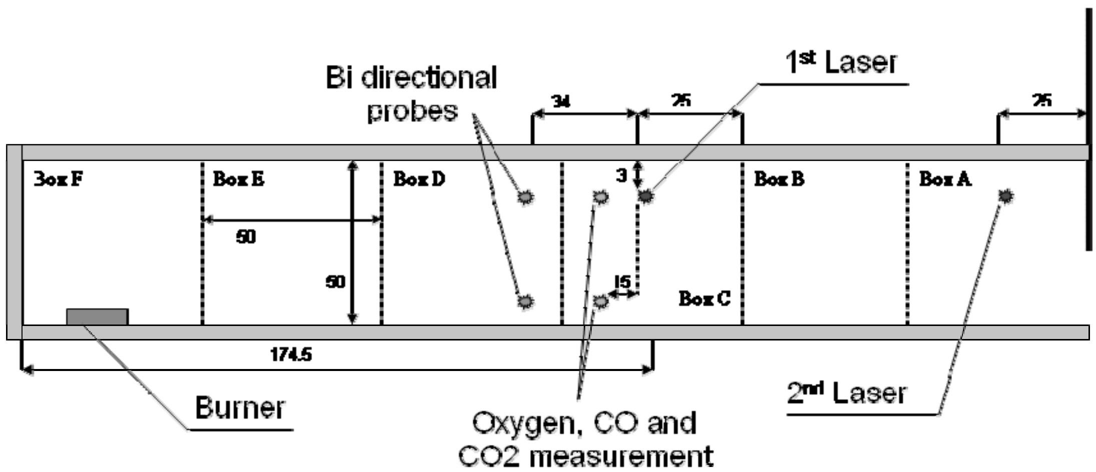

Figure 1. Side view of the experimental compartment and instrumentation. (All dimensions are in centimetres)

Experimental measurements

During the experiments the following measurements were made:

a) Gas temperatures inside the compartment by thermocouples (Type K, stainless steel sheath thermocouples with bare beads size 1.5 mm) inside each of the cubic boxes.

b) Total heat release rate obtained by placing the compartment under a calorimeter hood [9]. In order to eliminate the drift of the paramagnetic analyser, a methodology described in [10] was applied to correct the oxygen readings.

c) Gas velocities at two locations by bi-directional probes as shown in Fig. 1 mounted to measure flows along length of the corridor .

d) Species (O_2, CO, CO_2) concentrations at two locations using gas analysers as shown in Fig. 1.

e) Smoke concentration obtained from light extinction measurements in the exhaust duct (0.4m diameter) with a 632.8 nm He-Ne laser, 3mW. The signal from the laser beam was passed through a beam splitter in order to monitor intensity fluctuations [11].

f) Smoke concentration at two locations inside the enclosure (see Fig. 1 for locations). Two laser smoke meters were used. The first one was supplied by Thorlabs, whereas the second by DarkStar Ltd. Both are of the same type (red He-Ne) but with different powers (the former has 12mW whereas the latter 3mW). In order to balance the differences in power, two different load resistors were used to bring the readings to similar level. The reverse biased photodiode was used with no amplification in order to reduce any possible noise. Data logging unit consisted of 16 bits analogue – digital converters (manufactured by ICPDAS) and was sampled with integration time of 60ms and logged in 1 sec intervals.

Smoke measurements were based on light extinction. The light extinction coefficient k (m^{-1}) is determined as [12]:

$$k = \frac{1}{L}\ln\left(\frac{I_O}{I}\right) \tag{1}$$

where L is the path length through smoke, which is 0.4 m in the duct and 0.62 m in the enclosure, and I_o/I the non-dimensional ratio of the intensity of incident light to the intensity of transmitted light.

From the light extinction coefficient, smoke volume fraction can be calculated [13]:

$$f_v = \frac{k}{\sigma_s \cdot \rho_{soot}} \tag{2}$$

where f_v is the smoke volume fraction *(used units yielded f_v in parts per million, ppm)*, σ_s the mass specific extinction coefficient, which was taken as 8 m^2/g for propane [14] and ρ_{soot} the density of soot particulates generated from propane taken as 1.9 g/cm^3 [15].

If the flow rate is known as is the case in the duct, smoke yield can be calculated *(grams of smoke/grams of fuel burnt)* [11]:

$$y_s = \sigma_f / \sigma_s \tag{3}$$

where y_s is the smoke yield *(g/g)*, σ_f is the Specific Extinction Area on fuel mass loss basis *(SEA_f) (m^2/g)* , which can be calculated as [16] :

$$\sigma_f = k\dot{V} / \dot{m}_f \tag{4}$$

where $\dot{V}$ is the volumetric flow rate through the duct *(m^3/s)*, which was corrected to ambient conditions and $\dot{m}_f$ the mass loss rate of fuel *(kg/s)*.

Repeatability and uncertainties of measurements

In order to establish repeatability and uncertainties (defined as +/- standard deviation) of measurements, three tests at the same conditions were repeated for smoke inside the exhaust duct and two for smoke inside the enclosure. Figure 2a and 2b show, respectively, the smoke yield in the duct and smoke volume fraction in the enclosure from these repeatability tests. The repeatability is generally reasonable considering the difficulties in measuring smoke concentration. A summary of the uncertainties from these tests is shown in Table 1, along with those for other measurements.

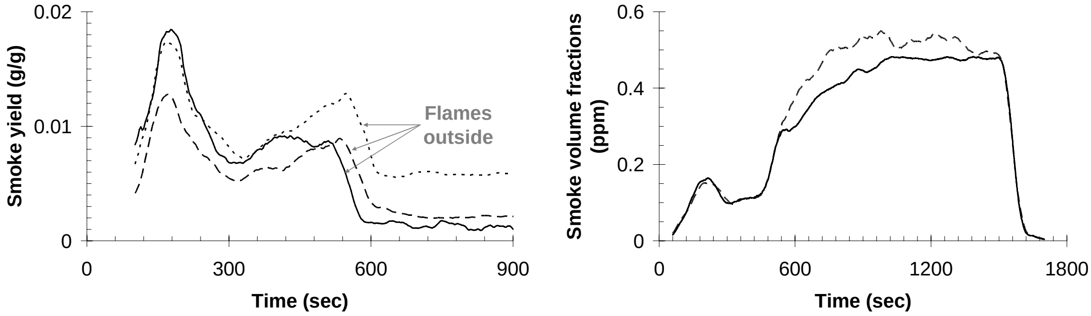

Figure 2. Repeatability of smoke yields a) in the exhaust duct and b) smoke volume fractions inside the enclosure.

Table 1. Summary of uncertainty analysis for all the measurements in this work.

	Type A Uncertainty, u_i	Type B Uncertainty, u_i	Combined Uncertainty u_c
Temperature			-6.5% to 2.5%
Accuracy of K type Thermocouple		+/- 2.5%	
Re-radiation losses		-6% to 0%	
Smoke volume fractions in the corridor			+/-17.8%
Calibration filters		+/-5%	
Repeatability of light extinction coefficient measurements	+/- 9.9%		
Soot density		+/-1.3%	
Mass specific extinction coefficient σ_s		+/-13.8	
Smoke volume fractions in the duct			+/-17.8%
Calibration filters		+/-5%	
Repeatability of light extinction coefficient	+/- 10 %		
measurements		+/-1.3%	
Soot density		+/-13.8	
Mass specific extinction coefficient σ_s			
Smoke yields in the duct			+/-12.3%
Calibration filters		+/-5%	
Repeatability of light extinction coefficient	+/-10%		
measurements		+/-5%	
Exhaust flow rate			
Heat Release Measurements (analyser drift included)			+/- 7.8%
Exhaust Flow Rate		+/-5%	
Accuracy of gas standards for calibration		+/-5%	
Instruments Uncertainty		+/-1%	
Random		+/-3%	

	Type A Uncertainty, u_i	Type B Uncertainty, u_i	Combined Uncertainty u_c
Global Equivalence Ratio determination Equiptment Uncertainty Fuel purity m_a=$AH^{1/2}$ formula	 -15 to 0%	 +/-1% +/-5%	-15.8% to 5.1%
Velocity measurements inside Pressure measurements Gas temperature Probe factor	 -6.5% to 2.5%	 +/-1% +/-6%	-8.9% to 6.6%
Gas Analyzers Zero and Span Gas Equipment Uncertainty Mixing and Averaging Random		 +/-5% +/-1% +/-3% +/-3%	+/-6.6%

Results and discussions

Before the results on smoke are presented, it is necessary to discuss briefly the HRR and how the Global Equivalence Ratio (for the period before external burning) was derived.

Heat Release Rate (HRR) **and** ***Global Equivalence Ratio***

Heat Release Rate measurements were made by oxygen consumption calorimetry [17] and compared with the supply of propane gas. Amount of supplied fuel was constantly monitored and yielded information about theoretical *HRR* obtained by multiplying amount of gas supplied *(g/s)* by chemical (effective) heat of combustion for propane, taken as 43.7 *kJ/g* [18]. Comparison of actual and theoretical *HRR* enabled us to obtain additional information about fire behaviour in corridor-like enclosure as discussed below.

A typical history of the *HRR* is presented in Figure 3. It can be seen that the theoretical and measured *HRRs* were close before an intermediate plateau was reached in the measured *HRR* (from about 200 to 560 seconds in Fig. 3). Averaging of this plateau yielded value which agreed (within measurement errors) with the maximum ventilated-controlled *HRR (kW)* (Eq. 5) [22-24]. The maximum *HRR*, which was possible for ventilation controlled burning inside the enclosure was derived by multiplying the ventilation controlled mass flow of air into the compartment [19-21] (Eq. 6) by the energy released per kilogram of air completely consumed inside (about 3000 kJ/kg):

$$HRR_{V\max} = 1500AH^{1/2} \tag{5}$$

$$\dot{m}_a = 0.5AH^{1/2}(kg/s) \tag{6}$$

where A (m^2) and H (m) are the area and height of the opening, respectively.

One may argue about the validity of Equation 6 for estimating the inflow of air before flashover as it is assumed to be valid only for post-flashover conditions. In addition, recent research [20] suggested overestimation of mass inflow via this approach for large openings. However, occurrence of this plateau confirmed that Equation 6 could be used for this case because measured values of HRR were in close agreement with HRR calculated from Equation 5.

That method of validation of Equation 6 enabled us to calculate the Global Equivalence Ratio *(GER)* [5] as:

$$\phi = HRR_{theoretical} / 1500AH^{1/2} \tag{7}$$

where $HRR_{theoretical}$ is the theoretical *HRR* derived from the known supply rate of propane and the denominator is the maximum *HRR* for the given opening size (HRR_{vmax} in Fig. 3). This calculation was derived from equitation proposed in [6] and employed in [22-24].

Calculation of the transient Global Equivalence Ratio via Eq. 7 confirmed that during this plateau fire was underventilated (gray-shaded area on Fig.3) . This underventilated condition ceased when flames emerged from the opening, confirmed by a sudden increase of the measured *HRR* to the value corresponding to the designed steady state *HRR.*

During the plateau period, flames existed only inside the compartment with excess unburnt gases escaping outside the compartment without burning. When flames outside the compartment were first observed the measured *HRR* suddenly increased to the value corresponding to the provided by the burner steady state *HRR*. The same behaviour was observed for all openings employed in this work. This behaviour was explained in [22,23], and was further discussed in [24].

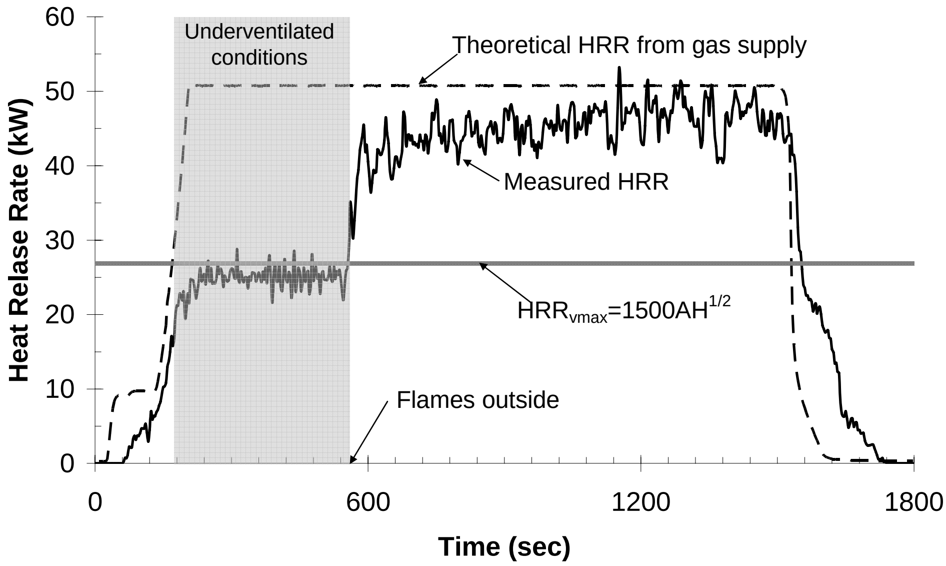

Figure 3. HRR history for the test having opening size 0.2m*0.2m and theoretical HRR = 50kW.

Smoke volume fractions measured in and outside of the enclosure

Figure 4 shows the smoke volume fraction inside and outside the corridor. Note that the smoke concentration in the duct is two orders of magnitude less than that in the enclosure because of the dilution of the gases in the exhaust duct. From Fig. 4 it can be noted that the concentration measured outside dropped significantly when external burning started for all the experiments whereas an opposite trend was noted for smoke production inside. For detailed discussion, smoke behaviour inside the corridor was divided into three phases:

Phase I - Shortly after ignition, the fire was well-ventilated as there was still enough air for complete combustion in the enclosure. During this period, smoke volume fractions increased with increase in *HRR* both inside and outside the enclosure.

Phase II – Immediately after fire became ventilation controlled (*GER>1*), there was a slight decrease of smoke volume fraction (both inside and outside). That difference was earlier explained in [13], i.e. initial peak of smoke volume fraction was associated with very rich conditions just after ignition.

Phase III – As soon as flame tip reached the opening, the HRR peaked off thus confirming that almost all released fuel was consumed. Conditions were no longer underventilated and the smoke volume fraction dropped outside, which suggests that external burning reduced amount of smoke. However, an increase was measured inside.

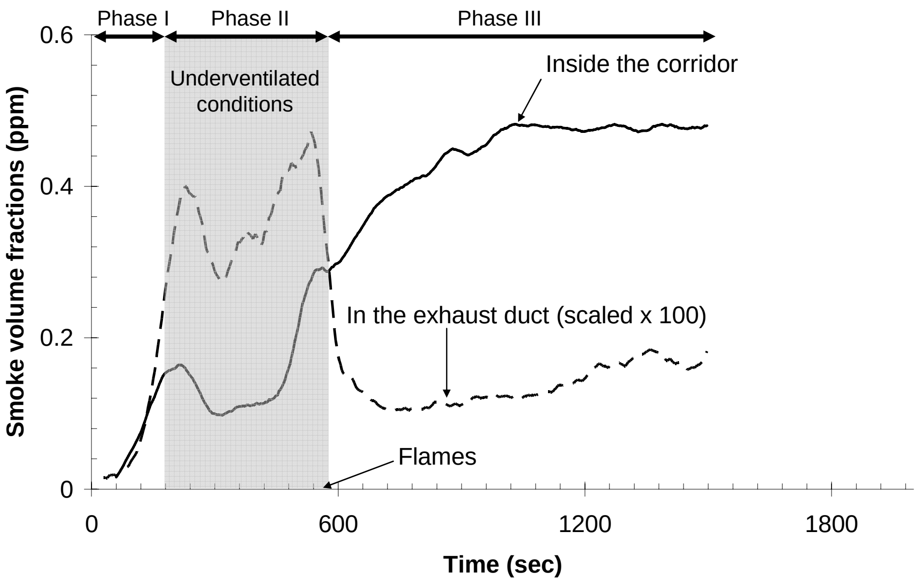

Fig. 4. Smoke volume fraction measured outside (in the exhaust duct) and inside (in the upper layer of third box). Opening size 0.2m*0.2m; Theoretical HRR = 50kW; Ventilation controlled HRR = 26.8kW

This phenomena was examined by comparing smoke volume fractions measured instantaneously at two different locations inside the corridor, in boxes A (close to opening) and C (middle section of the rig), as presented on Fig. 5. Values recorded in the box C were initially higher than these from Box A, whereas the opposite was seen after 594s. Similar observation was recorder for repeated tests.

In order to explain that smoke behaviour, closer examination of flame front movement was required. We were able to monitor it by overlapping upper layer temperatures measured in different boxes (Fig. 5). Peak values of that temperatures were shifted in time thus showed us the movement of flame front. This data confirmed visual observations that flame front was propagating through the corridor towards the opening. Moreover, sudden decrease of upper layer temperature in boxes far from the opening confirmed that flame was detached from the burner and travelled towards opening seeking fresh air.

Propagation of flame front through the corridor explained changes in smoke volume fractions after 594 seconds (Fig 5). At that time the smoke meter was passed by the flame front and whole buoyancy driven circulation of hot gases was altered inside. We have recorded a change of flow directions (Fig 6) at that time. Hot gases started to travel backwards towards the closed end of the corridor and thus contributed to smoke accumulation inside the enclosure. This change of flows and recirculation of combustion products was also confirmed by rapid decrease of oxygen levels measured in the bottom layer (middle of enclosure) as shown on Fig 6.

Factors affecting smoke behaviour

In this section, the effects of Global Equivalence Ratio, *(GER)*, Heat Release Rate *(HRR)* and opening size on smoke production will be examined. Smoke volume fractions weren't steady inside therefore no graphs will be presented comparing them directly as a function of GER, HRR or opening size as was not easy to choose corresponding time periods. Plots against time will be presented instead.

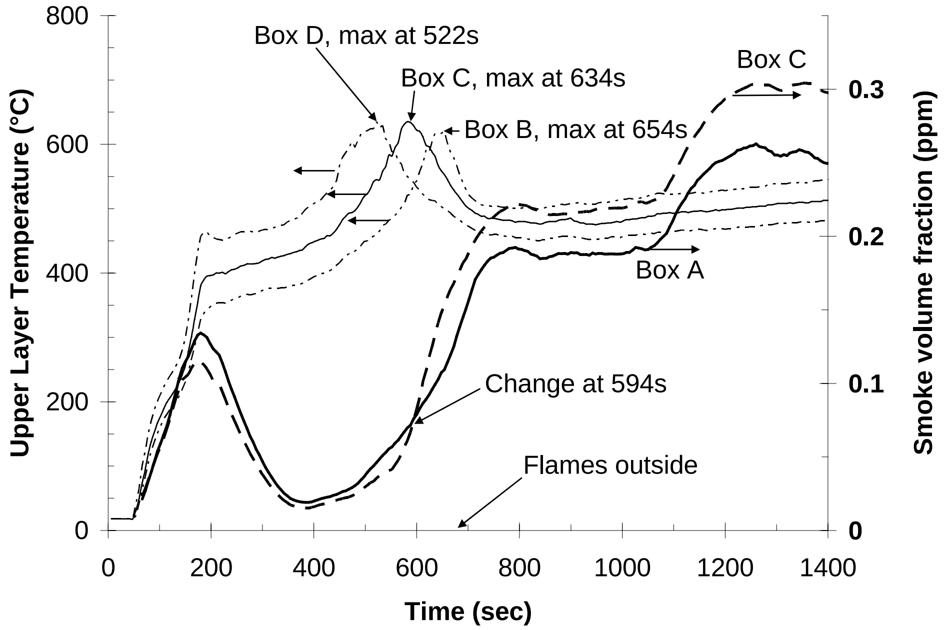

Fig 5. Smoke measured inside in two locations (right axis) plotted with upper layer temperature in three different locations (left axis). Opening size W0.1m*H0.25m. Theoretical HRR = 40kW, Ventilation controlled HRR = 18.75kW. Test with external burning at 667sec.

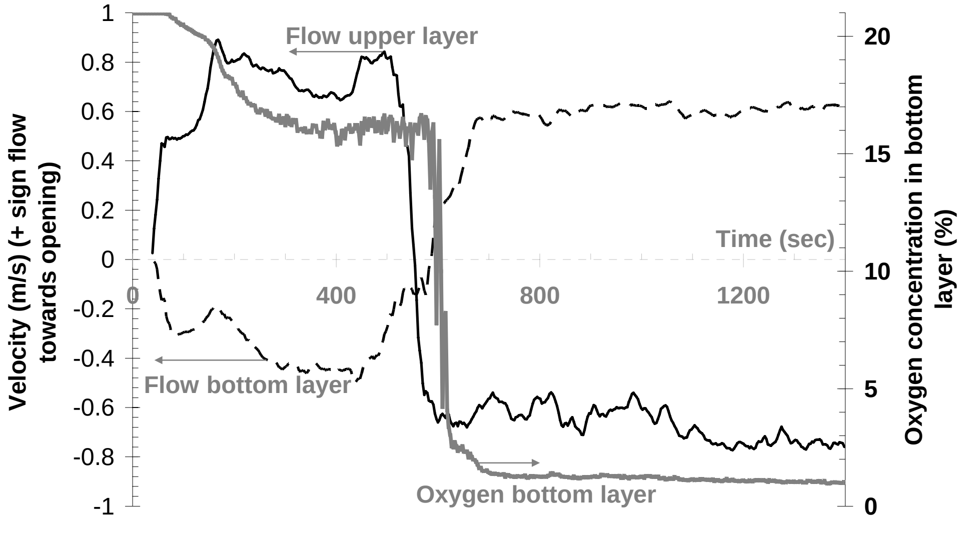

Fig 6. Velocity measurements in the middle of the corridor (box C) together with oxygen concentration in the bottom layer. Change in the direction of flows coincides with the transition of flame through box C.

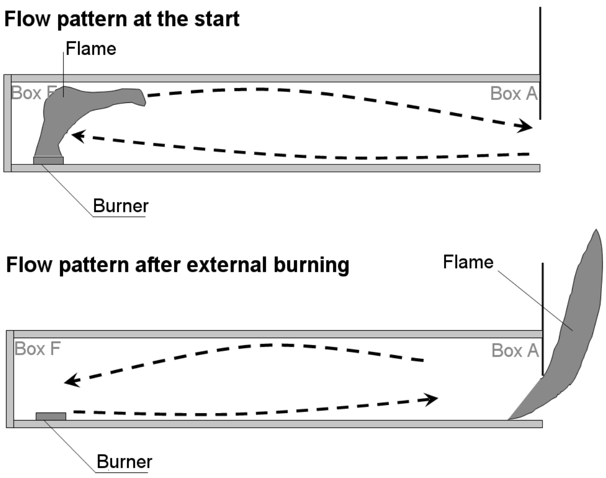

Fig 7. Change of flow patterns inside the corridor after external burning

Effects of GER

Firstly, we investigated effect of *GER* on the smoke production inside the enclosure. Tests were compared with similar *HRR*, but different *GER* (via different openings). Figure 8 presents smoke volume fraction as a function of time for two *GERs* (1.87 and 2.67) at about the same *HRR*. The general trends are similar to Figs. 4 and 5, characterised by a steady increase in Phase I, a slight decrease in Phase 2 and then a gradual increase in Phase 3 after flames come out the enclosure. This comparison showed that smoke concentration inside decreases with higher *GERs*.

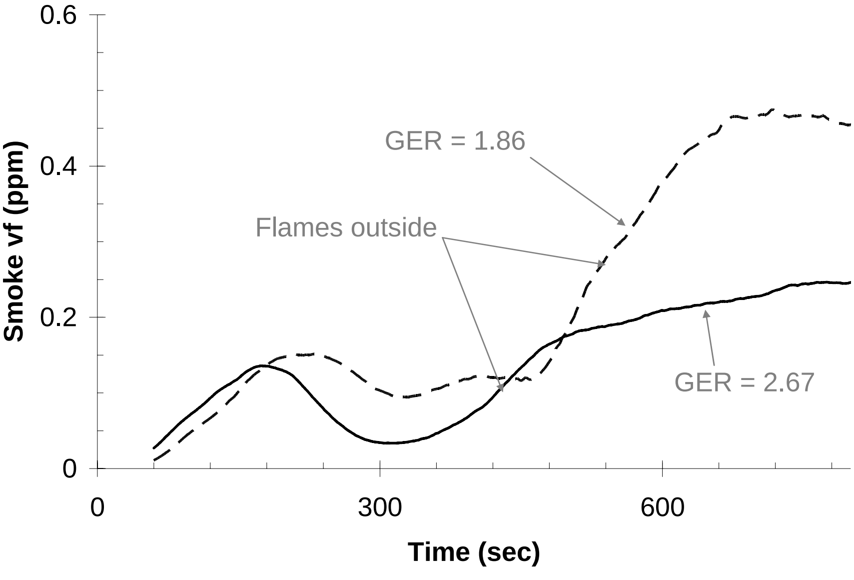

Fig. 8. Comparisons of smoke volume fraction for tests with similar HRRs but different GERs. Test 1: GER= 1.86, HRR_{gas}=50kW, HRR_{vmax}=26.8kW, Opening W20cm x H20cm. Test 2: GER= 2.67, HRR_{gas}=50kW, HRR_{vmax}=18.75kW, Opening W10cm x H25cm.

Effects of HRR

Figure 9 shows the smoke volume fraction for tests with same *GER* but different theoretical *HRRs*. Clearly, the *HRR* had a higher impact than the *GER*, as a change of *HRR* from 35 to 50 *kW* resulted in significant increase of smoke production. In order to explain these we will compare species concentrations, gas temperatures and velocity measurements between these two tests (Fig 10).

Figure 10 presents the upper layer oxygen concentrations measured in the middle of the corridor together with the ratio of carbon monoxide to carbon dioxide *(CO/CO_2)*. The ratio of CO/CO_2 has been widely used to indicate the extent of under-ventilation. Figure 10 shows that CO/CO_2 ratio increased after flames emerged from the opening meaning that the level of underventilation inside was higher than before external burning. That indicated that Global Equivalence Ratio was no longer a valid measure after external burning had started, even for measurements inside the corridor. It also confirmed that smoke production inside was governed by **a local** equivalence ratio, which was probably higher for test with 50kW as indicated by CO/CO_2 data.

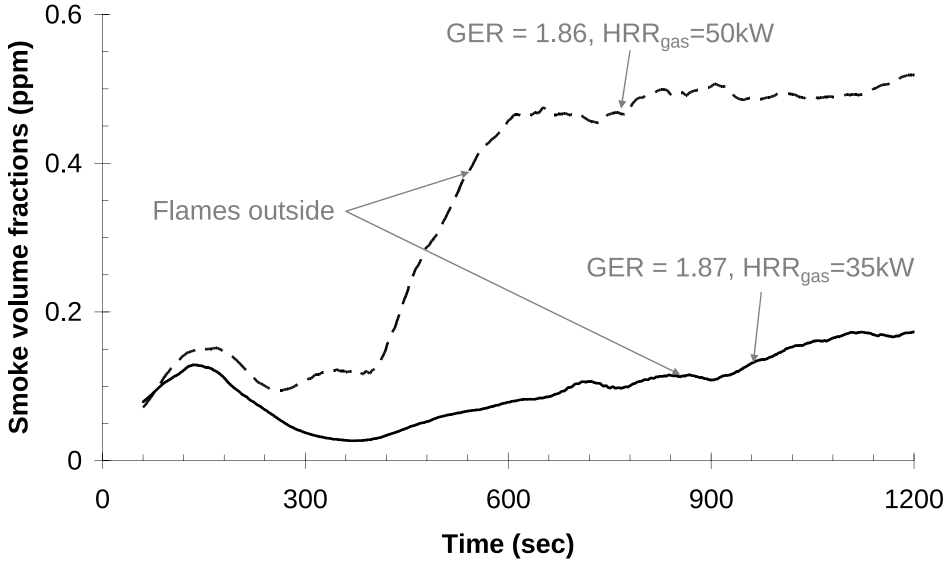

Fig. 9. Comparison of smoke volume fraction for tests with similar *GERs* but different *HRRs*. Test 1: GER= 1.86, HRR_{gas}=50kW, HRR_{vmax}=26.8kW, Opening W20cm x H20cm. Test 2: GER= 1.87, HRR_{gas}=35kW, HRR_{vmax}=18.75kW, Opening W10cm x H25cm.

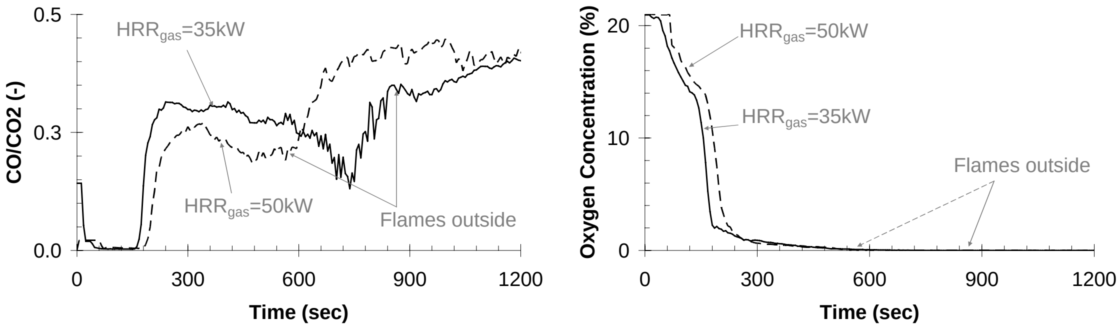

Fig. 10. Comparison of CO/CO_2 ratio (left) and oxygen concentration (right) measured in the upper layer for tests with similar *GERs* but different *HRRs*. Test 1: GER= 1.86, HRR_{gas}=50kW, HRR_{vmax}=26.8kW, Opening W20cm x H20cm. Test 2: GER= 1.87, HRR_{gas}=35kW, HRR_{vmax}=18.75kW, Opening W10cm x H25cm.

Conclusions

This work was aimed at experimental investigation of smoke production inside and outside of long corridor enclosures fires. The main conclusions are:

a) Three fire phases were distinguished: a) initial fuel rich fires burning inside, b) ventilation controlled fires burning inside, and c) ventilation controlled fires including external burning with combustion occurring near the opening. An intermediate plateau in the heat release rate *(HRR)* was observed during the ventilation controlled phases, This *HRR* (kW) is given by $1500AH^{1/2}$ [19, 22-24] where *A* and *H* were area and height of the opening, respectively.
b) Temperature and velocity measurements confirmed visual observations that the flame for underventilated conditions was propagating along the corridor towards the opening where it was anchored (see Fig.7). Moreover, a sudden decrease of upper layer temperature in boxes far from the opening confirmed that flames were detached from the burner and travelled towards the opening seeking fresh air.
c) After external burning is established with the flames moved to the open end of the enclosure, smoke concentration measured outside the enclosure decreases relative to levels measured before external burning is established (Fig. 4) . This decrease is due to complete combustion of the gases outside the enclosure. At the same time, concentration inside increases owing to accumulation of smoke. The increased smoke concentration inside the corridor is due to the nature of the flow behind the flame front, i.e. hot gases in the upper layer were travelling backwards toward the end of the corridor whereas cold gases were travelling in the lower layer towards the flame..This flow pattern is opposite to flow pattern ahead of the flame (see Figs. 6 and 7).
d) When external burning occurred, the global equivalence ratio (*GER)* is not the appropriate parameter governing smoke concentration inside the enclosure because conditions inside seemed to be more underventilated than indicated by *GER* as CO/CO_2 ratios show when measured inside before and after external burning (see Fig. 10).

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