Heat, CO and Smoke Release Rates of Plywood under a Depleted Oxygen Atmosphere: An Experimental Study Using an OSU Heat Release Rate Apparatus

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ABSTRACT

To obtain data for use in fire modelling for hazard assessment, a plywood sample was burned in a modified Ohio State University Release Rate apparatus. Both incident heat flux and oxygen concentration in the supplied atmosphere were varied and concentrations of oxygen, carbon monoxide, carbon dioxide were monitored during a 10 minute test period. Mass loss was measured at the end of the 10 minute period. The release rate and the total release of heat, carbon monoxide and smoke and the mean mass loss rate were calculated from the experimental data. By reducing the O_2 concentration, it was found that CO release increased suddenly at certain critical O_2 concentrations while heat and smoke release decreased. The smoke release and CO release were in contrast since when CO increased, smoke decreased. Ranges for O_2 concentration at which a transition from flaming to non-flaming would occur were estimated from the heat and CO release data. KEYWORDS: heat release, CO release, flaming, non-flaming, heat flux, transition, hazard, mass loss

INTRODUCTION

The use of fire modelling to assess the hazard associated with construction materials is of current interest at the Institute for Research in Construction, National Research Council of Canada. Parameters of interest for hazard analysis include the rates at which heat, smoke, and toxic gases are released under fire conditions. Such parameters, measured under oxygen depleted conditions, are required for modelling a room fire after its development. In this study, these parameters are experimentally measured for plywood using a modified Ohio State University (OSU) Heat Release Rate (HRR) apparatus. Oxygen concentration was varied from 21 to 8% and the incident heat flux varied from 30 to 50 kW/m².

Some data for the various hazard assessment parameters associated with wood materials burned under a depleted oxygen atmosphere were presented by Tewerson (burning rate, flame extinction)[1], Bankston and others (smoke)[2], and Tsuchiya & Sumi (smoke)[3]. These results will be discussed later in the paper.

MATERIALS AND METHODS

Material

The material used in this study was a 19 mm thick fir plywood (7-ply). Specimens, 150 mm by 150 mm, were conditioned at 22±1°C and 50±5% relative humidity (RH) for more than 48 hours. The density was 540 kg/m³ when conditioned. The moisture content was 6.7% measured after drying at 40 °C for 30 days.
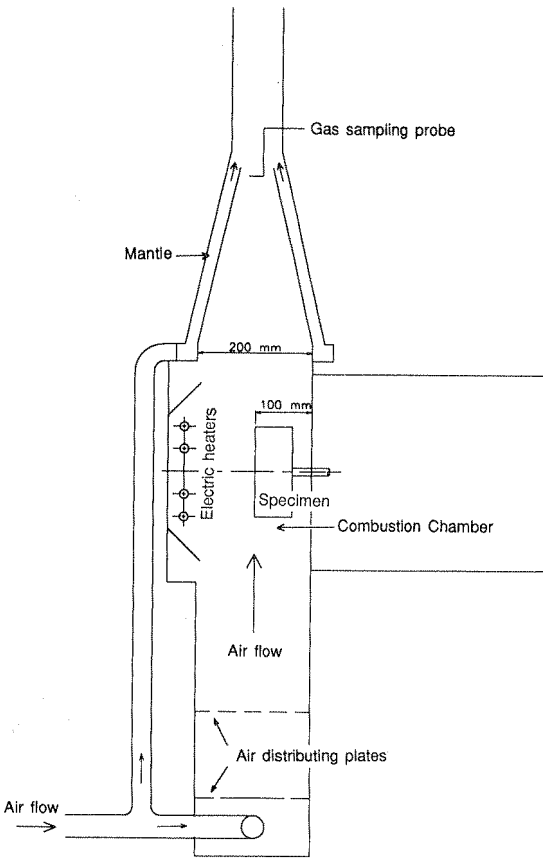
Fig. 1   Cross section of the OSU HRR apparatus

A proposed Degrees of Combustibility test apparatus[4] was used in this study. This is a version of the OSU HRR apparatus, with a modification made by the Federal Aviation Administration (FAA) in the U.S.A. for testing aircraft interior materials[5] and further modifications using the oxygen depletion principle developed by Huggett[6] and reduced combustion air. The cross section of the apparatus is shown in Fig. 1.

A specimen was burned in the vertical position (the wood grain was oriented vertically) under a specified level of radiant heat flux (30, 40 and 50 kW/m²).

A methane-air premixed horizontal flame of approximately 20 mm length from a pilot flame burner of a 6.3 mm outside diameter tube impinged on the lower part of the specimen surface at right angles to the surface. The upper pilot burner used in the FAA test was not used.

In the FAA test apparatus or the original ASTM E906[7], the airflow rate is fixed at 40 L/s (at atmospheric pressure and 23°C; this standard condition is used in this paper unless otherwise specified); in the present apparatus, it is controllable from 6.67 L/s to 40 L/s. In a preliminary study, varying the airflow rate within this range did not result in any significant change in the HRR (shown later), CO release or smoke release. In this study, the airflow rate was fixed at 13.3 L/s, which is 1/3 of the original ASTM E906 specification. The reduced airflow increased the concentration of combustion gases and oxygen depletion and thus enabled a greater analytical sensitivity and accuracy. For the present study, air or a mixture of air and N_2 was used.

O_2, CO_2, and CO concentrations were monitored throughout the experiment. A three-hole L-shaped sampling probe, positioned 50 mm below the upper edge of the combustion chamber walls, was used to sample the combustion gases (Fig. 1). This location was below the convergence point of the chamber airflow and the mantle airflow to assure that no mantle air was taken into the probe. A schematic of the complete gas analysis system is shown in Fig. 2.

A paramagnetic oxygen analyzer and non-dispersive infrared CO_2 and CO analyzers were used for the gas analysis. These analyzers were calibrated using atmospheric air and cylindered gas mixtures of O_2-N_2, CO_2-N_2, and CO-N_2.
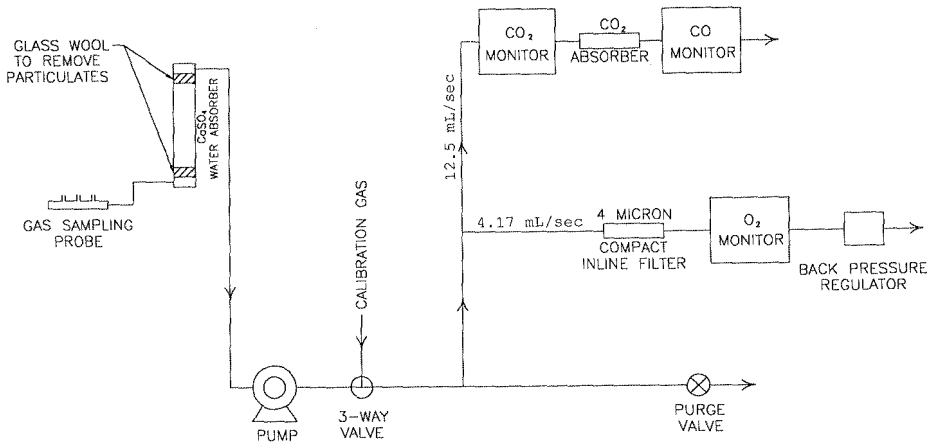
Fig. 2 Gas analysis system

The apparatus was calibrated for HRR using a square wave heat input by burning a prescribed flow of methane. The methane gas flow rate was 1 L/min (16.67 mL/s) for two minutes; it was then increased to 6 L/min (100 mL/s) and kept at that rate for two minutes. The sequence was repeated twice for one calibration. The original calibration burner specified in the ASTM E906 standard was used for this purpose. The calibration constant in kW/(O_2 depletion %), was calculated. The kW value in the calibration constant was calculated as the product of the methane flow rate under standard conditions and the net heat of combustion of methane.

For significant concentrations of CO, the O_2 depletion method for determining HRR must be corrected since the oxidation of carbon to CO results in a lower heat release than complete combustion to CO_2. A method for correcting the reduced HRR caused by CO generation has been presented previously[8].

Smoke concentration was measured using the light absorption method which is provided in the original ASTM E-906 test. The smoke release rate, Sr, was measured according to equation (1).

$$Sr = DFL^{-1}A^{-1} \tag{1}$$

where D is optical density, F is flow rate of hot combustion gas, m^3/s, L is light path, m, and A is exposed surface area of specimen, m^2. The measuring system was calibrated using 0.1 and 0.3 optical density filters. The exhaust gas temperature near the smoke measuring system was monitored with a thermopile. This temperature is required in the calculation of the volumetric flow of the exhaust gas.

The signals from the thermopile, smoke measuring system and O_2, CO_2, and CO analyzers were recorded using a data acquisition system. Data were recorded every second and averaged for 5 seconds. Concentrations of smoke, O_2, CO_2, and CO, the HRR based on O_2 depletion, and the corrected HRR based on CO release were calculated using the 5 second averaged data.

After a 600 second combustion period in each run, the burning specimen was extinguished by water spray. The specimens were dried in an oven at 40°C for one week and weighed to determine mass loss.

RESULTS AND DISCUSSION

In the OSU apparatus, the specimen burns in an enclosure and oxygen concentration and air supply
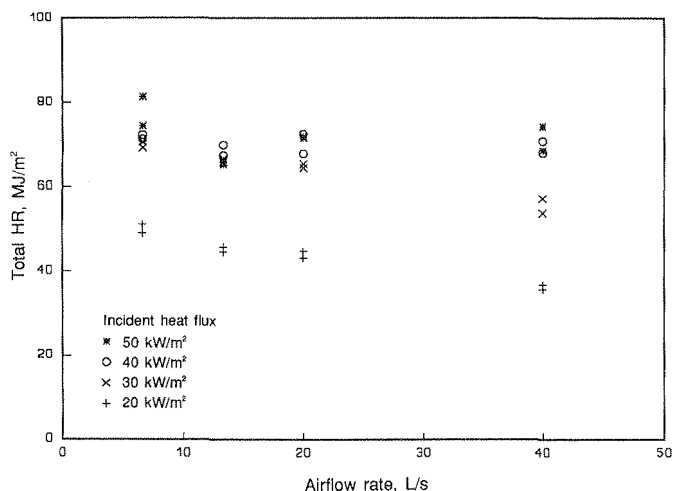
Fig. 3 Effect of air flow rates on HRR in a preliminary test

rates can be easily controlled.   This is one of advantages of the OSU apparatus over the cone calorimeter, which uses open burning.

The effect of air supply rates on combustion was studied in a preliminary investigation in this study in which a plywood sample was burned under 4 levels of incident heat flux (20, 30, 40 and 50 kW/m²) and 4 different airflow rates (6.67, 13.3, 20 and 40 L/s). The accumulated HR at 600 s is shown against airflow rates in Fig. 3.   The effect of air supply rates is minor except at combined low incident heat fluxes and high flow rates.

The airflow into the OSU apparatus is split between the combustion chamber and the mantle, with 1/4 flowing through the combustion chamber when the 40 L/s specified by the ASTM standard is supplied[7].   In the present experiment, where 13.3 L/s was supplied to the apparatus, the airflow to the combustion chamber was measured in two calibration runs performed before and after the series of combustion experiments.   In the combustion of CH_4, the molar flow rate of CO_2 is equivalent to the molar flow rate of supplied CH_4 and the molar flow rate of depleted O_2 is twice as much that of CH_4 as shown by the combustion equation (2).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{2}$$

When the mole fraction of CO_2 in the exhaust, Xco_2, is measured, the volumetric flow of air entering combustion chamber, Fc, can be obtained from equation (3).

$$Xco_2 = Fco_2/(Fc-Fo_2+Fco_2) = Fch_4/(Fc-Fch_4) \tag{3}$$

where Fco_2, Fo_2 and Fch_4 are the volumetric flows of CO_2, depleted O_2 and CH_4 respectively.   The measured ratios of combustion chamber flow and total flow (airflow splitting ratios) were 1/3.12 and 1/3.16.   In this calculation, water formation during combustion was not considered because the water was removed before the CO_2 concentration was measured. CO_2 in the atmospheric air was also ignored.   The airflow splitting ratio is required for the determination of the CO release rate.

The mole ratio of O_2/CO_2 is 2 in Equation (2). This ratio was verified in the two calibration runs to check the overall accuracy of the experiment.   Since concentrations of O_2 and CO_2 were measured in a dry gas mixture, the ratio was theoretically 1.79.   The experimental ratios were 1.90 and 1.89.

After a combustion period of 600 sec, the specimens were not completely carbonized and the wood structure remained on the unexposed side.   The percentage of mass loss ranged from 24% (under 30
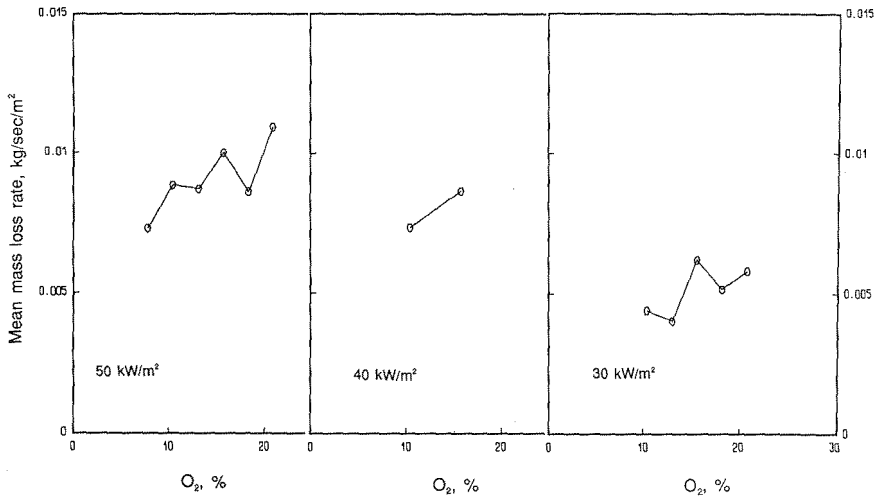
Fig. 4 Mean mass loss rates

kW/m² heat flux and low oxygen) to 66% (under 50 kW/m² and 21% oxygen). The mean mass loss rates for the 600 second tests are shown in Fig. 4.

The peak HRR and the total HR per mass loss for the 600 sec combustion tests are shown in Fig. 5. At high O_2 concentrations, the (total HR)/(mass loss) or the effective heat of combustion ranges from 13 to 18 MJ/kg, higher at higher heat flux levels; the values are close to the heat of combustion of wood materials that is from 16.7 to 18.5 MJ/kg[9]. For each incident heat flux, there is a critical O_2 concentration below which both HRR and HR significantly decrease.

The peak CO release rate and the total CO per mass loss are shown in Fig. 6. A sudden CO
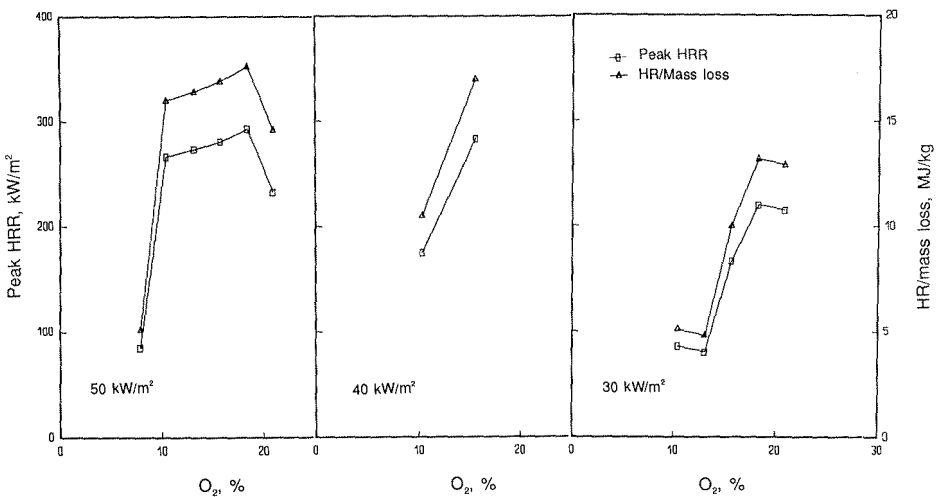

Fig. 5 Effect of O_2 concentrations on HRR and total HR per mass loss
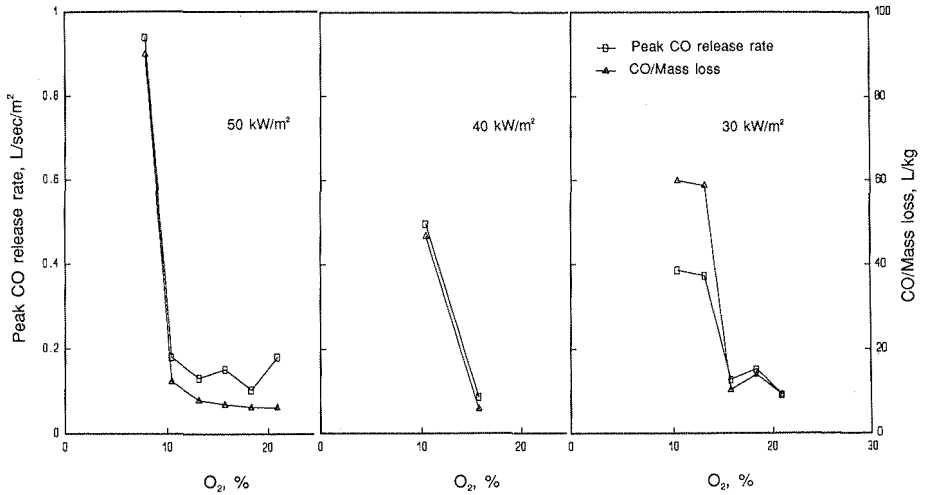
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Fig. 6 Effect of O_2 concentrations on CO release rate and total CO per mass loss

increase was observed for each level of incident heat flux below a critical O_2 concentration. The CO release may be related to the temperature of the combustion, but this has not been addressed in this paper. Both the peak CO release rate and the (total CO)/(mass loss) are important factors when fire gas toxicity is considered.

The oxidation of carbon to CO generates less heat than complete combustion to CO_2. The difference is 12.6 kJ/L. For the maximum 90 L/kg (total CO)/(mass loss) measured in the present study, the reduction in heat release relative to complete combustion is 1.1 MJ/kg. This reduction does not account for the difference in the (total HR)/(mass loss) measured with high and low O_2 concentrations. For example, the difference between the 1st and 2nd of the two left most points of (total HR)/(mass
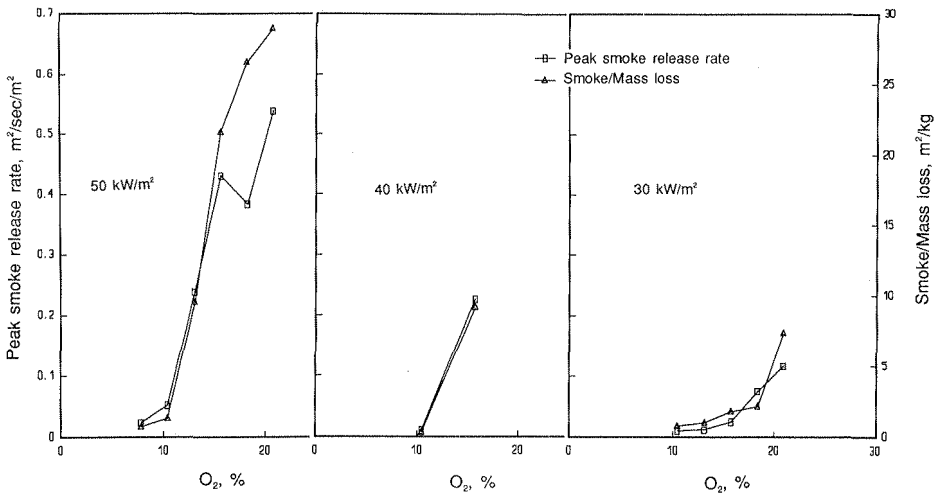

Fig. 7 Effect of O_2 concentrations on smoke release rate and total smoke per mass loss
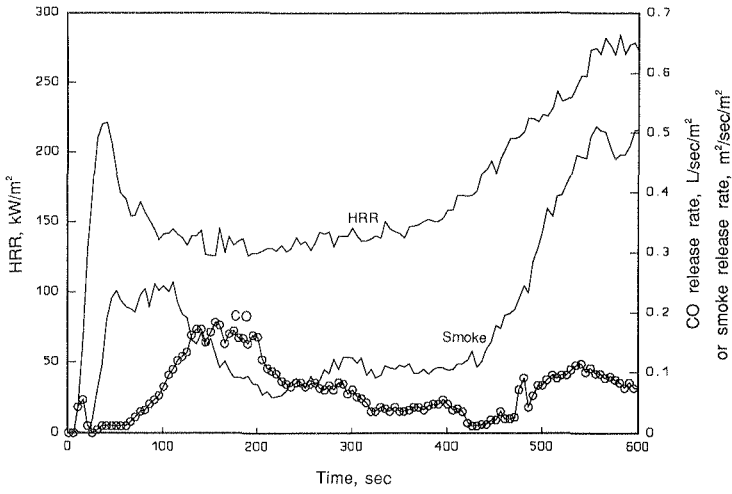
Fig. 8 Release rates of heat, CO and smoke, an example in 15.7% O_2 under 50 kW/m² incident heat
flux

loss) in Fig. 5 was 11 MJ/kg. This difference may be explained by the relative increase of a
hypothetical carbonization reaction (4) which results in mass loss without much heat output and an
abundance of carbon rich residue.

$$C_6H_{10}O_5 \rightarrow 6C + 5H_2O \tag{4}$$

In Fig. 7, the peak smoke release rate and the total smoke per mass loss are shown. It is notable
that, at any level of incident heat flux, smoke release was high for higher oxygen concentrations and vice
versa. This is in contrast to CO release shown in Fig. 6. In a study of wood smoke by Bankston and
others[2], a slight reduction of smoke particle weight in a 10% O_2 atmosphere compared with in air was
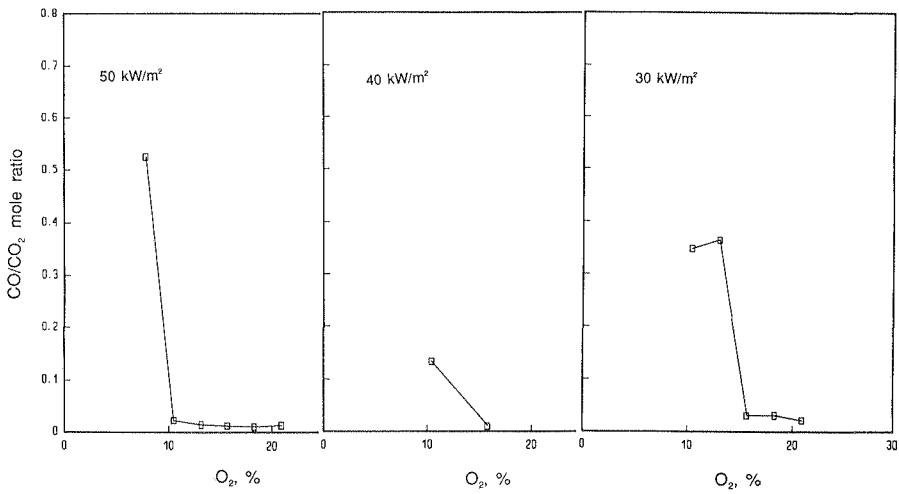

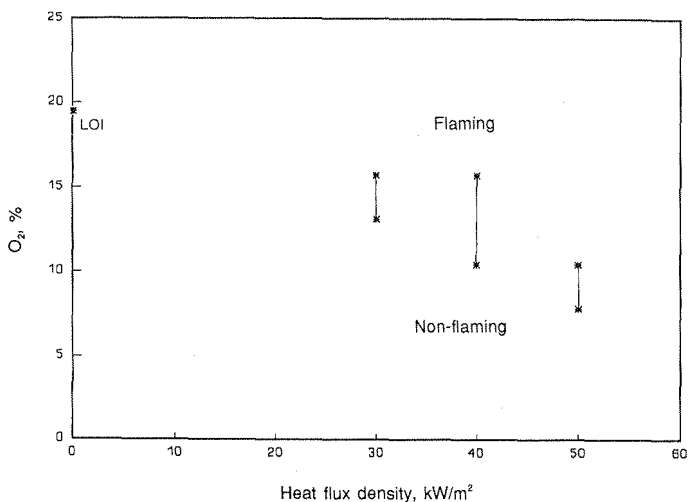Fig. 9 Effect of O_2 concentrations on CO/CO_2 ratio

Fig. 10 Ranges of transition from flaming to non-flaming

reported. In Tsuchiya & Sumi's smoke study using the dynamic method, some wood materials released more smoke in air and in N_2 than in a 1:1 air-N_2 mixture in terms of (total smoke)/(mass loss)[3].

As shown in Fig. 6 and Fig. 7, there is an opposite trend in CO and smoke release when the O_2 concentration is varied. Similar trends for CO and smoke release were also observed within each combustion test. In Fig. 8, the release rates of heat, CO and smoke in 15.7% O_2 under 50 kW/m² incident heat flux are shown as an example. CO and smoke were released at different stages of combustion especially as noted between 0 and 250 seconds in Fig. 8. Smoke and heat were released together. In Fig. 8, the time recorded for each sensor was adjusted by the time delay measured in the methane calibration run.

Transition of the Combustion Mode

Plywood burns with flames in air. When the O_2 concentration is reduced, there is a critical concentration below which flaming ceases and non-flaming or glowing combustion takes place. This transition occurred even though a pilot flame was always impinging on the specimen surface during the experiments. The transition was characterised by (a) a sudden reduction of HRR or a reduction in the (total HR)/(mass loss) and (b) a sudden increase in CO release or an increase in the CO/CO_2 ratio (Fig. 9). The ratio of CO/CO_2 is a parameter to characterize room fires (the inverse of this ratio may also be reported).

The transition between flaming and non-flaming combustion was related to both the O_2 concentration and incident heat flux. When the incident heat flux was lower, the transition occurred at a higher O_2 concentration. This is shown in Fig. 10 in which the limiting oxygen index (LOI) for plywood is also shown. The LOI is the transition point under zero irradiance. Tewarson[1] showed similar results for polymethyl methacrylate (PMMA) with quenching of the flame observed (there is no non-flaming combustion for PMMA). In his experiments, however, the incident heat flux density was below 16.7 kW/m².

Variation of Fire Parameters

Heat, CO and smoke release and CO/CO_2 ratio varied significantly by reducing the O_2 concentration

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of the combustion atmosphere. The variations, expressed in ratios of the maximum value and minimum value within the present set of experimental conditions, were as shown in Table 1.

Most significant variations occurred in the CO/CO_2 ratio and (total smoke)/(mass loss). The variation was larger in experiments with a higher heat flux. The major variation often occurred within a small range of O_2 concentrations. More study surrounding these O_2 concentrations is recommended. Such data are needed for modelling the hazard associated with developed room fires.

TABLE 1. Variation (maximum value/minimum value) of heat, CO and smoke release when the O_2 concentration was varied

Heat flux density kW/m²	Mass loss	Heat			CO			CO/CO_2	Smoke		
		(1)	(2)	(3)	(1)	(2)	(3)		(1)	(2)	(3)
50	1.5	1.4	4.5	3.4	9.1	9.5	14.4	49	23	41	61
40	1.2	1.5	1.9	1.6	5.8	6.9	8.2	13	22	31	36
30	1.4	3.3	3.9	2.8	4.2	5.0	6.6	17	12	10	13

Note to Table 1
(1) Peak release rate
(2) Total release at the end of 10 minutes test period
(3) Total release per mass loss

CONCLUSIONS

By decreasing the O_2 concentration, the total HR dropped rapidly at a critical O_2 concentration. The critical concentration depended on the incident heat flux. Corresponding with the decrease in the total HR, the total CO release increased. These changes are caused by the transition from flaming to smouldering.

By decreasing the O_2 concentration, the total smoke release decreased. The high smoke release corresponded with low CO release. Similar trends were observed within a single combustion experiment in reference to time. CO and smoke were released at different stages of combustion.

The transition of flaming to non-flaming combustion depended on both the incident heat flux and O_2 concentration. Under 50 kW/m² incident heat flux, the transition occurred at approximately 10% O_2 concentration and without incident heat flux, at 19%.

More experimental studies are needed to determine the hazard factors for room fires under O_2 depleted conditions. It is particularly important to further investigate the vicinity of critical O_2 concentrations at which the transition of the combustion mode and resulting significant variations in hazard factors take place. Such data are required to assess the hazards associated with developed fires.

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