Combustion Behaviour of Polyurethane Foams under Depleted Oxygen Environment

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ABSTRACT

In building fires, fuel is often exposed to reduced oxygen environments at various radiation levels. However, combustion behaviour under depleted oxygen environments during fire has not been investigated systematically. In this study, a cone calorimeter was reconstructed in order to control the combustion atmosphere. The supply oxygen level in the cone calorimeter varied from 10 to 21%. Three commonly used polyurethane foams were tested in experiments. The imposed radiation level varied from 10 to 20 kW/m^2. It was found that whilst both the radiation heat flux and the oxygen concentration affected most fire behaviour parameters the oxygen concentration had less effect on ignition time.

KEYWORDS: Cone calorimeter, reduced oxygen environment, ignition time, fire development, and experiments.

INTRODUCTION

The cone calorimeter is a bench-scale heat release rate apparatus based on oxygen consumption [1,2]. It is a useful tool for measuring the various properties needed to assess the fire hazard of materials or products, such as the characteristics of ignition [3,4], charring [5], CO/CO_2 ratios [6] and smoke [7,8]. All these applications are carried out under the free-burn conditions and the oxygen content is close to 21% in the combustion zone. However, in building fires, and especially in post-flashover fires, it has been found that the concentration of oxygen in the fire region or the fire room can be much lower than 21% [9].

Flame spread on the surface of solid fuel such as furniture strongly depends on the concentration of oxygen nearby [10]. In order to simulate flame spread more closely it is necessary to investigate the combustion behaviour at all relevant levels of oxygen

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concentration. Cone calorimeters with controlled-atmosphere have been designed and used to simulate an oxygen-depleted environment [11] and oxygen-enriched environment [12]. However, the effects of oxygen concentration on the behaviour of flame spread have not been investigated systematically.

For this study, a standard cone calorimeter was re-constructed. Nitrogen was used as diluent to ambient air. The oxygen concentration can be controlled from 21% down to about 5%. A series of experiments has been conducted with this new cone calorimeter at CSIRO, Highett, Australia. The present paper reports part of the experimental results, including the effect of the levels of oxygen and radiation on the ignition time and fire progress of three flexible polyurethane foams used in either domestic or contract furniture.

MODIFICATION AND CALIBRATION OF THE CONE CALORIMETER

Reduced oxygen atmospheres were obtained by introducing nitrogen into the air supply to the apparatus. (Figure 1).

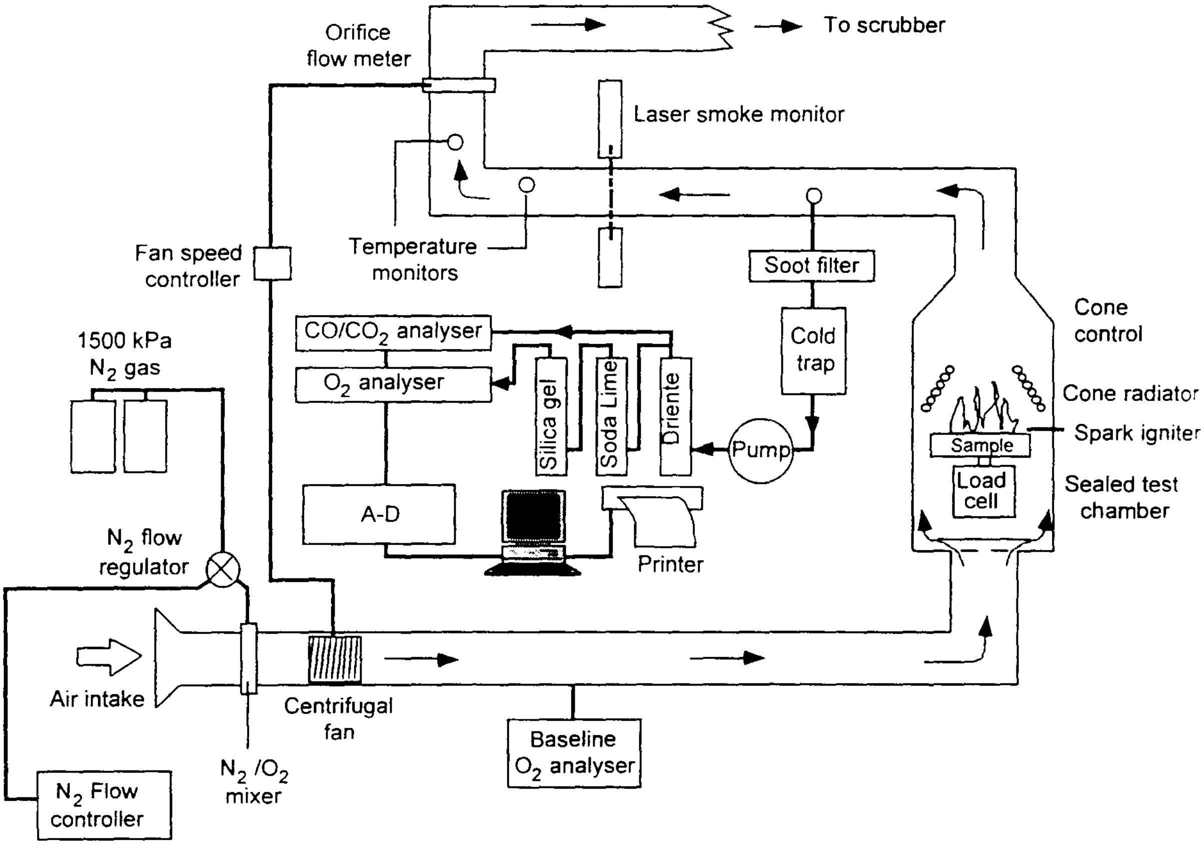

Figure 1 Schematic of the cone calorimeter after modification

The "Stanton Redcroft" (now "Rheometrics") Cone Calorimeter which we are using originally had an unsealed combustion chamber enclosed by glass doors on three sides and a blank metal partition on the fourth. The combustion chamber had to be isolated from the laboratory environment by installing diaphragms and seals around the exhaust hood, cables and tubes.

nd around the weighing bench for the load cell. New catches and seals were needed for the oors. The modified apparatus still complies with ASTM E1354 [13]

he inlet air system is designed to be used in both controlled-atmosphere and normal peration. In previous controlled-atmosphere Cone Calorimeters [11,14,15,16], the air flow 'as controlled by an exhaust fan and the pressure inside the test chamber was lower than the mbient. This is believed to have created some difficulties in balancing the systems. Therefore was decided to relocate the fan to the inlet side of the combustion chamber. This produces a ery slight positive pressure both in the combustion chamber and in the exhaust system.

'he nitrogen is mixed with ambient air via a manifold prior to passing through the inlet fan. t this stage of development there is no temperature control on the inlet air, though this is itended. A feedback control was installed between the measured exhaust flow and the inlet an in order to compensate for gas production during combustion.

'he inlet oxygen concentration is monitored by an in-situ sensor, which gives instantaneous eadings and allows the use of a feedback controller on the nitrogen supply. Air enters the ombustion chamber through a perforated plate beneath the load cell, baffled to prevent raughts in the combustion zone.

fter the modifications to the cone calorimeter, calibration experiments were carried out in tandard conditions to ensure that the apparatus was still giving the same results as before the odification. Figure 2 gives the experimental results of PMMA slabs under the conditions of 1% of oxygen and 50 kW/m^2 of imposed radiation heat flux. It is seen that the performances

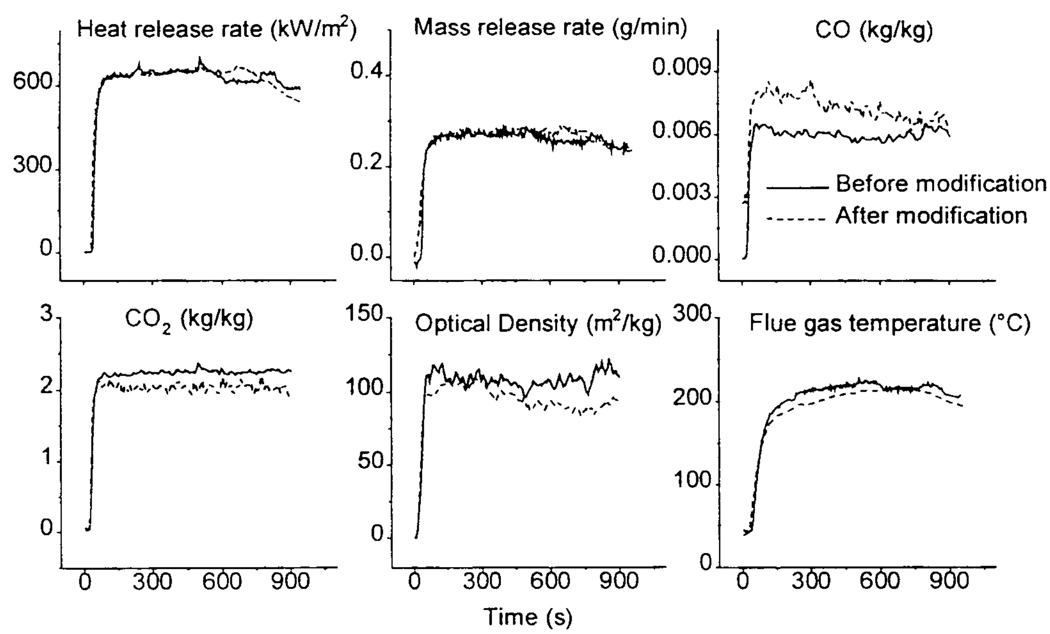

Figure 2 Calibration of the modified cone calorimeter in standard conditions with PMMA slab

of the modified cone calorimeter are generally similar to those of the standard cone calorimeter. The differences of all parameter are less than 10% except for CO. The reason for this discrepancy is being investigated. There were virtually no changes in heat release rate, mass release rate and the rise of flue gas temperature. However, the ratio of CO/CO_2 was increased.

Introducing a specimen into the sealed combustion chamber in the normal way causes changes in the controlled atmosphere. In previous controlled-atmosphere Cone Calorimeters this problem was overcome by placing a water-cooled shutter between the specimen on the load cell and the radiant heater and allowing the atmosphere to equilibrate before exposing the specimen [11,14]. In the CSIRO apparatus one of the glass doors was replaced with a panel containing a glove. Under reduced oxygen conditions the operator opens a door and places the specimen inside the chamber away from the cone heater. The door is closed and once the atmosphere has equilibrated the specimen is lifted into place by the operator using the glove.

Changes were also made in the way the optical system for smoke measurement was kept clean. Previously external air was induced to flow across the lenses by the slight negative pressure in the exhaust duct. In the modified apparatus purge air is introduced.

FOAM SAMPLES AND EXPERIMENTAL PROCEDURE

The specimens were three grades of flexible polyurethane foam; Dunlop standard Foam A23-130, Dunlop fire-retarded foam Stamina ST32-80 and Dunlop high-resilience foam Endura EN36-100. The foams were cut into blocks 100×100×50 mm. The specimens were tested wrapped in aluminium foil after being conditioned to constant weight at 23 °C and 50% relative humidity. Specimens were introduced into the combustion chamber by the procedure described previously. The density and hardness of these three samples are listed in Table 1.

Experiments were conducted according to ASTM 1354 [13], which is technically identical to ISO 5660 with the addition of smoke measurement. All experiments were conducted in the horizontal orientation using the edge frame, but no wire grid. A large number of experiments has been carried out using the modified cone calorimeter. In the present paper, [illegible] experimental results are reported which cover the variation of radiation heat flux (10, 15 and 20 kW/m^2), oxygen concentration (21, 15 and 10%) and the three types of polyurethane foams. All experiments were carried out under conditions of piloted ignition.

RESULTS AND DISCUSSIONS

Ignition Time

Ignition time is defined as the difference between the time of exposure of a specimen to a certain level of radiation and the time of the appearance of a sustained flame. For those experiments in which the ignition did not occur, the was continued for 10 minutes. Each experiment was carried out in triplicate and the mean and standard deviation of each are provided in Table 1. For the cases where ignition did not occur, duplicate experiments were conducted.

It is clear that the radiation level strongly affects the time to ignition. When the radiation heat flux reaches 20 kW/m^2, the specimen ignited instantaneously (in about 6 sec). It seems that the effect of oxygen concentration on the ignition time is a discontinuous function. If the oxygen concentration is higher than 10% (15 and 21% in this study), the ignition time is independent of the oxygen level. However, when oxygen concentration is down to 10%, the specimen does not ignite even though the radiation level increased from 10 to 20 kW/m^2. There must exist a transition region between 10 and 15% of oxygen where the ignition time is very sensitive to the oxygen concentration. This issue will be investigated in the future.

For an environment of 21% oxygen and a fixed level of radiation heat flux (10-20 kW/m^2), there is no significant difference in the ignition time between the three polyurethane specimens.

Table 1 Effect of radiation level, oxygen concentration on ignition times

Test No.	Polyurethane	Radiation level (kW/m^2)	Time to sustained† flaming (s)	Foam properties: Density, Hardness (kg/m^3, Newton)
Oxygen concentration in environment 21%				
1	Dunlop standard Foam	10	45±1.4	
2	A23-130	15	13±1.4	22-24, 110-140
3		20	6±0.0	
4	Dunlop fire-retarded	10	43.5±2.1	
5	foam Stamina ST32-	15	14.5±0.7	32-34, 70-95
6	80	20	6±0.0	
7	Dunlop high-resilience	10	36.5±2.1‡	
8	foam Enduro EN36-	15	12.5±2.1	36-38, 85-110
9	100	20	6.7±1.6	
Oxygen concentration in environment 15%				
10	Dunlop standard Foam	10	51±5.6[ii]	
11	A23-130	15	13±2.0	
12		20	5.5±0.4[ii]	
Oxygen concentration in environment 10%				
13	Dunlop standard Foam	10		
14	A23-130	15	No ignition§	
15		20		

† Mean and standard deviation for three replicates unless otherwise stated
‡ Mean of two replicates as the 3rd replicate did not ignite within 10 min.
§ Two duplicates did not ignite within 10 min.

Fire Development

The experimental results of fire development of the three specimens under differen conditions are given Figures 3-6. In Figures 3-5, the oxygen concentration remains at 21% The radiation level was set at 10, 15 and 20 kW/m^2 respectively. It was found that except foi the ignition time, the variation in radiation had very little effect on the fire development foi the standard polyurethane foam specimen (see Figure 3). If the ignition time was taken intc account (compared with the case of 20 kW/m^2, 7 s delay for the 15 kW/m^2 case and 39 s delay for the 10 kW/m^2 case), the values of the measured parameters followed the similar traces except for CO, where the maximum value of CO concentration for the case of 20 kW/m^2 was about 10% higher than the other two cases.

The radiation level, however, significantly affects the fire development for the other two polyurethane foams. Figure 4 depicts the experimental results of fire-retarded foam. On reducing the radiation heat flux from 20 kW/m^2 to 15 kW/m^2, the fire development changed slightly. For instance, the peak heat release rate reduced less than 10%. However, when the radiation heat flux was reduced to 10 kW/m^2, the peak heat release rate decreased to 30% of that of the previous two cases. The total mass consumed was about 15.1 g (71% of the original specimen) for each of the former two cases and about 2.1 g (10%) for the later.

Figure 5 demonstrates the results of the high-resilience foam . When the radiation reached 20 kW/m^2, the peak heat release rate reached 300 kW/m^2 and 68% of the foam was consumed. When the radiation levels were reduced from 15 and 10 kW/m^2, the fire development performed similarly. The peak heat release rates were down to 80 kW/m^2 and less than 2% of the foam was consumed in each of these two cases.

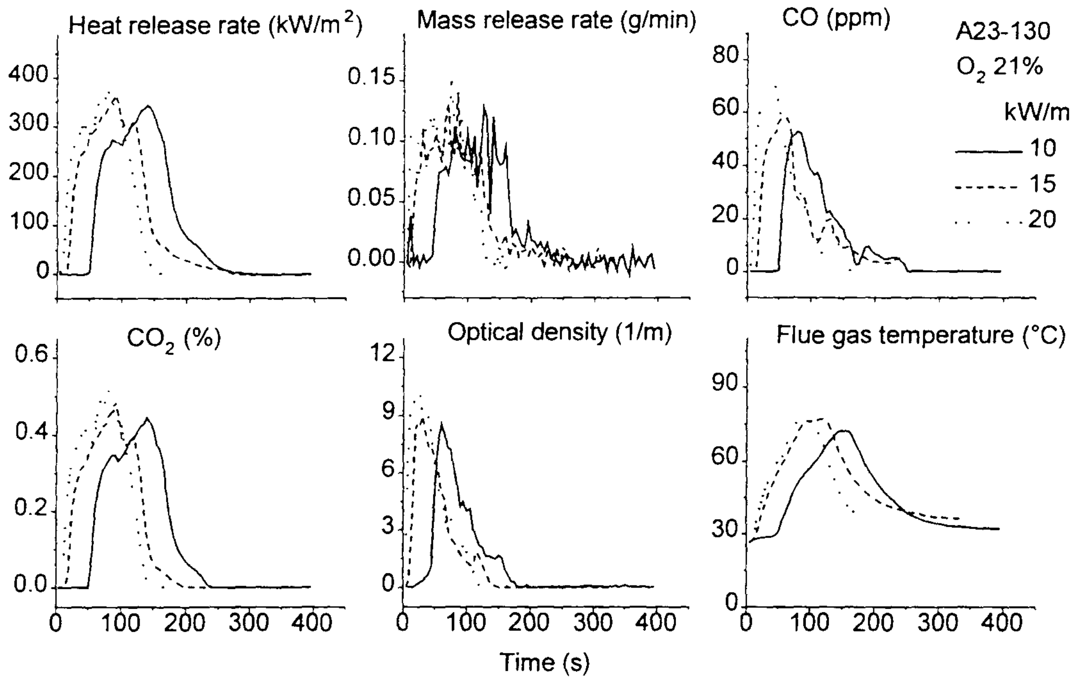

Figure 3 Fire development over standard polyurethane foam (A23-130) under conditions of 21% of oxygen and various radiation level

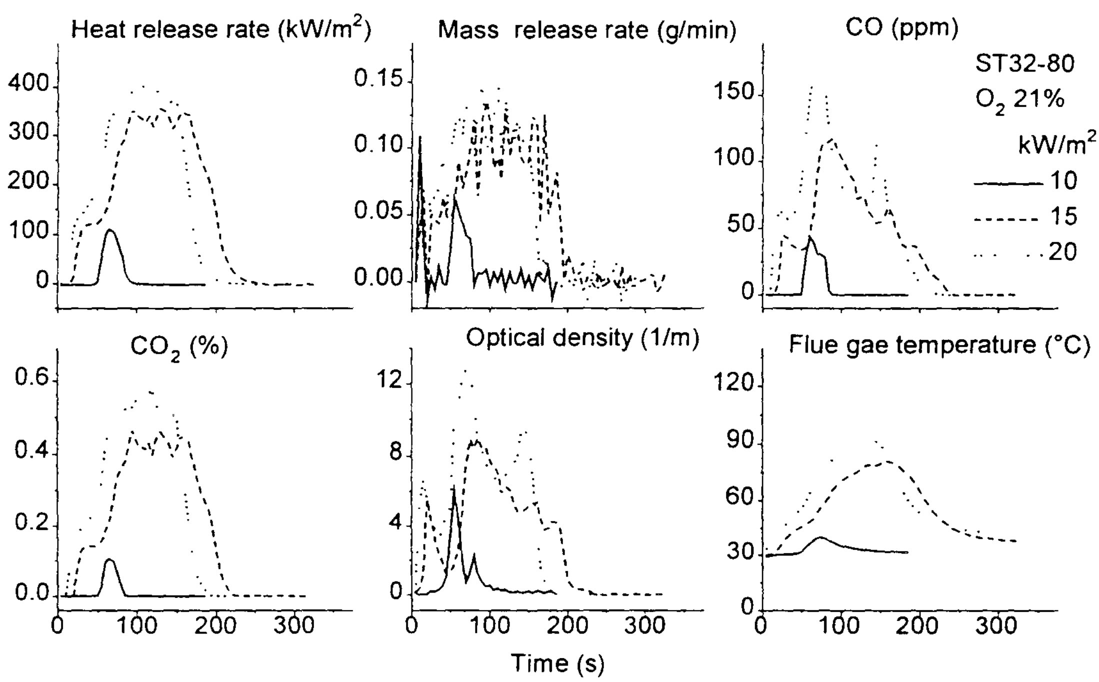

Figure 4 Fire development over fire retarded polyurethane foam (Stamina ST32-80) under conditions of 21% of oxygen and various radiation level

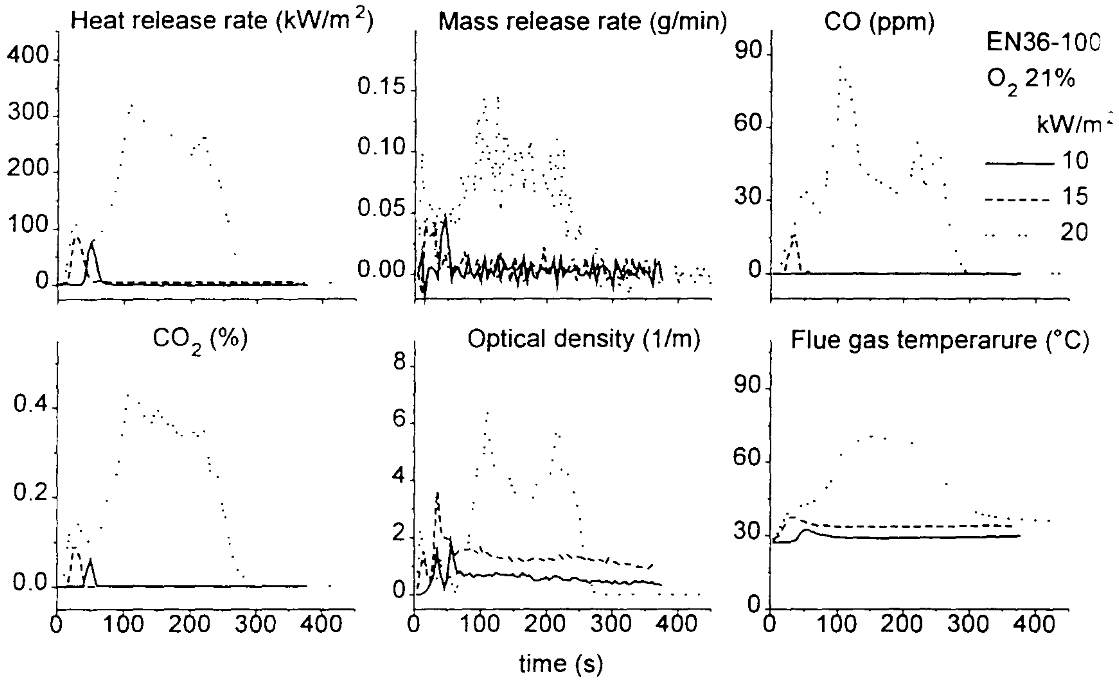

Figure 5 Fire development over high-resilience polyurethane foam (Enduro EN36-100) under conditions of 21% of oxygen and various radiation level

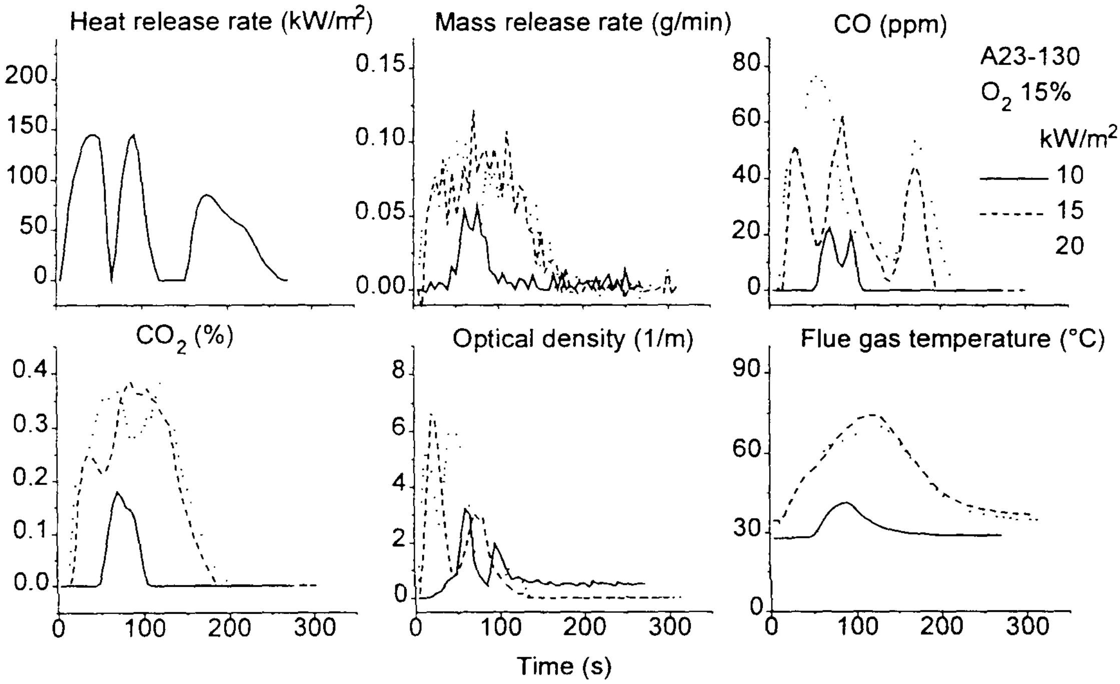

Figure 6 Fire development over standard polyurethane foam (A23-130) under conditions of 15% of oxygen and various radiation level.

In this study, only the standard foam was assessed under the reduced oxygen condition. When the oxygen concentration was reduced to 15%, radiation level significantly affected the fire development (Figure 6). As the software monitoring of baseline oxygen concentration has not been fully implemented, it is not yet possible to accurately determine rates of heat release. However other parameters are readily determined. It was found from the plot of mass loss rate and other parameters that the fire development was in the similar track when the radiation level remained at 15 or 20 kW/m^2. About 60% of the foam was consumed in these two cases. When the radiation reduced to 10 kW/m^2, the fire intensity decreased significantly. In total, 15% of the foam was consumed.

CONCLUSIONS AND RECOMMENDATIONS

A standard cone calorimeter has been re-constructed to operate under oxygen concentrations which can vary from 21% to lower than 10%. The performance of the modified cone calorimeter under the standard operating conditions has been verified using PMMA. .

In general, the radiation heat flux level significantly affects the ignition time. It seems that ignition time varies with the level of radiation heat flux when the oxygen concentration level remains at 15% or higher to 21%. When the oxygen concentration level is down to 10%, the specimens of polyurethane could not be ignited.

It was found that the radiation level significantly affects the fire development for all three foams when the oxygen concentration is reduced to 15%. When the oxygen level is increased to 21%, it seems that the radiation level does not affect the fire development for the standard foam.

The experimental results reported in this paper revealed that when the oxygen concentration was reduced to 10%, the polyurethane foam could not be ignited if the radiation level was at or below 20 kW/m^2. It is expected that if the radiation heat flux is increased to 50 kW/m^2 or higher, the polyurethane foam would ignite even when the oxygen level was reduced to lower than 5% [9].More experiments will be carried at oxygen concentration between 10 to 15% to investigation the ignition time. The experimental program is under way. More results will be published.

ACKNOWLEDGMENT

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