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Effect of oxygen concentration on the combustion of horizontally-oriented slabs of PMMA

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ABSTRACT

The aim of this study is to collect data on the combustion of horizontally-oriented poly(methyl methacrylate) (PMMA) samples in reduced oxygen atmospheres for CFD model validation. Experimental results relating the oxygen concentration to the burning behavior of 3-cm-thick clear PMMA slabs are discussed. Experiments are conducted in the controlled atmosphere calorimeter of IRSN called CADUCEE. Pyrolysis and combustion of 0.2×0.2 m^2 horizontally-oriented PMMA samples are studied varying the oxygen molar fraction from 0.210 to 0.180, extinction occurring at about 0.175. The measured quantities are the regression rate of the slab, mass loss rate, temperatures and total and radiative heat fluxes at the center of the slab. All experiments are carried out twice, showing a good repeatability. It is found that the slab regression rate, mass loss rate and heat fluxes at the slab center decrease significantly with the oxygen concentration, while the gas temperature is much less sensitive. Most notable is that the radiative and convective contributions to the total heat flux remain almost constant, respectively 0.65 and 0.35. It is also found that both heat fluxes and mass loss rate exhibit linear oxygen-concentration-dependent behavior. From an energy balance and current average values of the total heat flux and regression rate at the center of the slab, the present study obtains a heat of gasification value of 2.25 MJ kg^{-1}, in agreement with literature data.

1. Introduction

The effect of oxygen on fuel combustion is of primary importance for fire safety in nuclear plant compartments as well as buildings. The oxygen quantity available for combustion depends on the oxygen consumption by the fire and on the air renewal rate of the mechanical ventilation system or openings. Under-oxygenation of the ambient air will lead to a decrease of the heat flux feedback from the flame to the fuel surface, which in turn will lead to a decrease in mass loss rate (MLR). This is accompanied by changes in other properties, such as the regression rate of the slab, gas temperature and composition, and total and radiative heat fluxes.

A model developed by Utiskul *et al.* [1] may be used to express the MLR as a function of the oxygen molar fraction. This model was based on the Quintiere approach [2] and some simplifying assumptions. By assuming a small B number and neglecting the flame radiative effects, Utiskul et al. obtained the following relationship

$$\dot{m}''_{X_{O_2}} = \dot{m}''_{21}\frac{X_{O_2}}{0.21} + \frac{\dot{q}''_{ext,r}}{L_G} \tag{1}$$

More recently, Nasr et al. [3] developed a model to determine the fuel mass loss rate in a confined and mechanically ventilated compartment fire using a global approach. This model was based on the energy balance at the fuel surface without neglecting the radiative heat flux from the flame and considering that the term ln(1+B)/B is different from 1. They obtained the fuel mass loss rate as

$$\begin{aligned}\dot{m}''_{X_{O_2}} = {} & \frac{h_{conv}}{L_G c_p}\frac{ln(1+\mathrm{B})}{\mathrm{B}}\left[Y_{O_2}\frac{\Delta h_c}{r}(1-\chi_r) - c_p(T_s - T_\infty)\right] + \frac{\sigma\varepsilon_f}{L_G}(\alpha \mathrm{Y}_{O_2} + \eta)^4 \\ & + \frac{\sigma}{L_G}(1-\varepsilon_f)(T_g^4 - T_s^4) - \frac{\sigma}{L_G}(T_s^4 - T_\infty^4)\end{aligned} \tag{2}$$

Few correlations have been established to express the MLR as a function of the oxygen concentration from experimental results. Tewarson and Pion [4] determined the MLR of various commercial samples of plastics, at a small scale, in normal and reduced-oxygen atmospheres. For a limited range of molar fraction of oxygen, they found a linear correlation between the MLR and the oxygen concentration for all the combustibles studied

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Nomenclature

B	Spalding number (–)
c_p	Specific heat at constant pressure (J kg^{-1}. K^{-1})
CHF	Convective heat flux at the center of the slab (W m^{-2})
h_{conv}	Convective heat transfer coefficient (W m^{-2} K^{-1})
L_G	Heat of gasification (J kg^{-1})
$\dot{m}''$	Mass loss rate per unit of area (kg m^{-2} s^{-1})
MLR	Mass loss rate (kg s^{-1})
$\dot{q}''$	Heat flux per unit of area (W m^{-2})
r	Stoichiometric oxygen to fuel mass ratio (–)
RHF	Radiative heat flux at the center of the slab (W m^{-2})
T	Temperature (K)
THF	Total heat flux at the center of the slab (W m^{-2})
X	Molar fraction (mol mol^{-1})
Y	Mass fraction (kg kg^{-1})

Greek

α	Nasr model parameter
γ	Blocking factor (–)
$\dot{\delta}$	Regression rate of the burning surface at the center of the slab (m s^{-1})
Δh_c	Heat of combustion (J kg^{-1})
ε	Emissivity (–)
η	Nasr model parameter
ξ	Tewarson empirical parameter
ρ	Density of PMMA (kg m^{-3})
σ	Stefan-Boltzmann constant (W m^{-2} K^{-1})
χ_r	Flame radiative fraction (–)

subscripts

21	Oxygen concentration of 21%
∞	Ambient
cp	Condensed phase
e	Extinction
ext	External
f	Flame
F	Fuel
g	Gas
l	Lost
N_2	Nitrogen
O_2	Oxygen
r	Radiative
rr	Re-radiation
s	Surface
v	Vaporization

$$\dot{m}''_{X_{O_2}} = \frac{\xi}{L_G} X_{O_2} + \frac{\dot{q}''_{ext,r} - \dot{q}''_l}{L_G} \tag{3}$$

More recently, a study of Peatross and Beyler [5] has been conducted on compartment fires using either natural or overhead forced ventilation. Diesel, wood cribs and polyurethane slabs have been used as fuels. The experimental results have shown a well-mixed compartment in terms of oxygen concentration, regardless of the ventilation rate, and a two-layer or linear variation of temperature depending on the scenario. From these results and those of Tewarson *et al.* [6] and Santo and Tamanini [7], Peatross and Beyler developed a linear correlation between the MLR normalized by its value in free atmosphere and the oxygen concentration

$$\frac{\dot{m}''_{X_{O_2}}}{\dot{m}''_{21}} = 10.0 X_{O_2} - 1.1 \tag{4}$$

This correlation shows a good agreement with small-scale (from 0.007 to 0.07 m^2) and real-scale (from 0.3 to 0.55 m^2) experimental results for diesel, heptane and PMMA fires.

The present study aims at investigating the effect of oxygen on the burning of horizontally-oriented PMMA slabs. While many experiments have been carried out on the combustion of PMMA slabs in vertical or inclined orientation (see for example, Pizzo et al. [8], Chen et al. [9] or Drysdale and Macmillan [10]), very few have been performed on horizontally-oriented PMMA slabs configurations and even less in reduced oxygen atmospheres. Rhodes and Quintiere [11] conducted tests on burning rate and flame heat flux for horizontally-oriented black PMMA in a cone calorimeter. Linteris *et al.* [12] studied the burning of black PMMA samples in small scale in the cone calorimeter. They carried out experiments in two orientations (horizontal and vertical) in free atmosphere with an imposed radiant heat flux up to 75 kW m^{-2}. Beaulieu and Dembsey [13] made some experiments on the effect of oxygen on flame heat flux in horizontal and vertical orientations for black PMMA, propylene and black polyoxymethylene (POM) in enhanced ambient oxygen concentration, from 21% to 40%. Kacem et al. [14] performed experiments on square PMMA slabs with a side length of 0.1, 0.2 and 0.4 m in free atmosphere. Table 1 summarizes the configurations found in the literature for the burning of horizontally-oriented PMMA samples.

The Controlled Atmosphere Device for Unburnt and Carbon Emission Evaluation (CADUCEE) [15] is used to conduct experiments at ambient oxygen concentrations below 21.0%. This device, designed and built by IRSN, allows to carry out experiments on solid, liquid and gaseous fuels at small and intermediate scales. Clear PMMA is here used as fuel. This non-charring polymer, with relatively well-known thermophysical properties, is sometimes used as containment windows for glove boxes in nuclear facilities. The aim of this study is to collect data on the combustion of horizontally-oriented PMMA samples in reduced oxygen atmospheres for model validation.

2. Experimental setup

2.1. Calorimeter CADUCEE

Experiments described here are conducted in the calorimeter CADUCEE. This device allows to study the combustion of small and intermediate-scale fuel materials in controlled-oxygen atmosphere (Fig. 1). The air/nitrogen mixture is injected from the floor into the 22 m^3 combustion chamber, leading to a versatile oxygen concentration in the range of [0.0 – 21.0%]. Further details about the CADUCEE facility, its metrology and associated uncertainties can be found in [15]. For the current experiments, the oxidant supply and exhaust flow rates were set to 1500 m^3 h^{-1} and 2500 m^3 h^{-1} respectively.

Table 1
Literature studies on the burning of horizontally-oriented PMMA samples.

References	Material	Area (m^2)	Oxygen concentration (%vol.)
Tewarson et al. [6]	Clear PMMA	0.0068–0.073	16.6–46.5
Santo et al. [7]	Clear PMMA	0.071	18–20.9
Kacem et al. [14]	Clear PMMA	0.01; 0.04; 0.16	21
Linteris et al. [12]	Black PMMA	0.01	21
Rhodes et al. [11]	Black PMMA	0.01	21
Beaulieu et al. [13]	Black PMMA	0.009–1.17	20.9–40