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# Experimental investigation of the impact of oxygen flux on the burning dynamics of forest fuel beds

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ABSTRACT

To characterize the burning dynamics of porous wildland fuels it is fundamental to understand the heat and mass transfer mechanisms. These are significantly different compared to solid fuels and less well documented. Radiation feedback from flames and convective heat transfer from forced airflow have been found to influence the pyrolysis and combustion processes. Smoldering combustion and resulting heat feedback is also shown to have significant impact. The link between burning dynamics and the oxygen availability is also explored. Combustion experiments are carried out using the FM Global Fire Propagation Apparatus in order to investigate changes in the burning behavior of porous fuel beds as a function of the oxygen availability. The oxygen flux into the combustion zone was varied by three mechanisms, (1) varying natural entrainment, (2) changing forced flow magnitude and (3) oxygen concentration. Results investigated from the combustion tests were the duration of flaming (from which the average burning rate was deduced), CO and $CO_2$ generation rates, combustion efficiency and heat release rate. For both test series, the duration of flaming decreased and peak heat release rate increased with increasing oxygen flux. For tests with varying flow magnitude the combustion efficiency stayed constant with a $CO/CO_2$ ratio below 1.5%. For tests with varying flow oxygen concentration the ratio was much higher, between 12% and 26%, indicating high levels of incomplete combustion. At a given oxygen flux, changes in heat flux feedback from the flames, convection cooling, and combustion efficiency were found to be the reason for differences on the order of 30–50% in burning rate and thus heat release rate. The intensity of smoldering increased with increasing oxygen flux equally for both tests series. The study explored herein provides insight into importance of several heat and mass transfer mechanisms that govern the burning dynamics of porous wildland fuel beds. Furthermore, it also highlights the necessity of understanding incomplete combustion (flaming) in the wildfire context.

## 1. Introduction

This experimental study explores the impact of ventilation conditions on the burning behavior of porous wildland fuels. It is based on the development of the FM Global Fire Propagation Apparatus (FPA) as a research tool to investigate the flammability of porous wildland fuels. The FPA is a bench scale calorimeter developed by FM Global to perform material flammability assessments in a standardized environment. The procedure employed here is based on ASTM E2058 [1] with certain adaptation to accommodate wildfire research needs. Previous studies [2–7] have demonstrated the applicability of this apparatus to investigate forest fuel burning dynamics. The versatility of this apparatus allows the study of the critical factors that influence the burning dynamics, such as fuel and bulk properties, heating rate, airflow magnitude, and oxygen ($O_2$) concentration.

In order to understand wildfire behavior globally, it is paramount to understand which physical mechanisms are important. The fundamental mechanisms of heat and mass transfer drive the ignition and combustion processes of forest fuel beds and thus wildfire spread and intensity. Heat transfer dominates the heating of the fuel bed and the onset of pyrolysis. Gaseous pyrolysis products then need to mix with available oxidizer in order to form a flammable mixture. If pyrolysis produced at sufficient rate these volatiles will reach the lower flammability limit (LFL) and in the presence of a pilot or at sufficiently high temperature undergo exothermic combustion.

It becomes evident that fire spread, if associated to the ignition time [8], is strongly dependent on the burning behavior of the fuel. Mass transfer of oxygen to the reaction zone dominates the behavior of a flame front and hence the intensity of the combustion, which in turn provides the heat feedback to the adjacent unburned fuel, i.e. the

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**Nomenclature**

| | |
|---|---|
| *CV* | control volume |
| *d* | length (cm) |
| $EF_x$ | Emissions factor of species X (g $kg^{-1}$) |
| *F* | forced convection |
| *FMC* | fuel moisture content (d.w.) |
| *FPA* | FM Global Fire Propagation Apparatus |
| *HF* | high flow (100 lpm, 13.4 cm $s^{-1}$) |
| *HOC* ($\Delta h_c$) | Heat of combustion (kJ $g^{-1}$) |
| *LF* | low flow (50 lpm, 6.7 cm $s^{-1}$) |
| *m* | mass (kg) |
| *NF* | no flow (0 lpm) |
| *NT* | no quartz tube is used |
| *OC* | oxygen consumption calorimetry |
| *PS* | Pinus strobus (White pine) |
| *(p)HRR* | (peak) heat release rate |
| *T* | refers to use of quartz tube |
| *TOC* | transition oxygen concentration |
| *V* | volume ($m^3$) |
| *y* | oxygen concentration (by volume) |

*Greek*

| | |
|---|---|
| $\alpha$ | volumetric ratio (-) |
| $\rho$ | density (kg $m^{-3}$) |
| $\sigma$ | surface area to volume ratio ($m^{-1}$) |
| $\chi$ | combustion efficiency (-) |

*Subscripts*

| | |
|---|---|
| *b* | burning rate |
| *eff* | effective |
| *g* | volumetric ratio of gas (porosity) |
| $O_2$ | $O_2$ conc. or oxygen flow rate (g $s^{-1}$) |
| $O_{2,n}$ | oxygen flow rate due to entrainment |
| $O_{2,f}$ | forced oxygen flow rate |

*Superscript*

| | |
|---|---|
| (*) | bulk |
| (•) | rate ($s^{-1}$) |

mechanisms of heat transfer and mass transfer are strongly coupled.

Besides the flame heat flux feedback, solid phase combustion (smoldering) is also strongly dependent on the oxygen availability [9,10]. Increased rates of smoldering will increase the local solid phase temperature, which increases heat losses via radiation.

Both mechanisms, heat flux from flames and the increased rate of smoldering, increase the burning rate, which provides the required fuel vapor for combustion. This feedback can be described as a feedback loop and illustrates the inherent linkage between heat and mass transfer. The focus of this work will be on three mechanisms by which the ventilation condition is altered: entrainment area, forced flow magnitude and $O_2$ concentration. As described above varying either one of these parameters will inherently impact the combustion dynamics and thus also the wildfire behavior. Varying the forced flow magnitude is analogous to changing the wind speed condition during wildfire (e.g. [11]), manipulation of the oxygen concentration relates to the availability of oxygen inside the fire front (the inclusion of higher concentrations allows the influence of this parameter to be more completely understood). Porterie et al. [12] have shown a region of reduced oxygen environment within and around a spread wildland fire in their simulations. The changes in the entrainment area relate to changes in flame shape.

Varying the oxygen mass flow rate in the combustion zone will affect the flaming regime of the combustion of fuel beds [13–17]. Variation in burning dynamics can be dramatic resulting in transition from diffusion to premixed burning as the oxygen availability decreases. As a result, reaction chemistry and heat flux feedback from the flames changes. The change is mainly attributed to alteration in atmospheric heat capacity due to the presence of dilution gas (e.g. nitrogen as is the case here). The flame temperature reduces when oxygen concentration in the atmosphere decrease. It reduces until a limiting temperature is reached. Below this threshold, combustion will cease, due to insufficient energy. It is highlighted in [16] that the gas used for the dilution is important and will impact the flame temperature and thus extinction condition.

To investigate the role of oxygen flux on the burning behavior of typical porous wildland fuels, an experimental approach is developed using White pine needles as the porous fuel. Visual observations, analysis of the duration of flaming, CO and $CO_2$ generation rates,

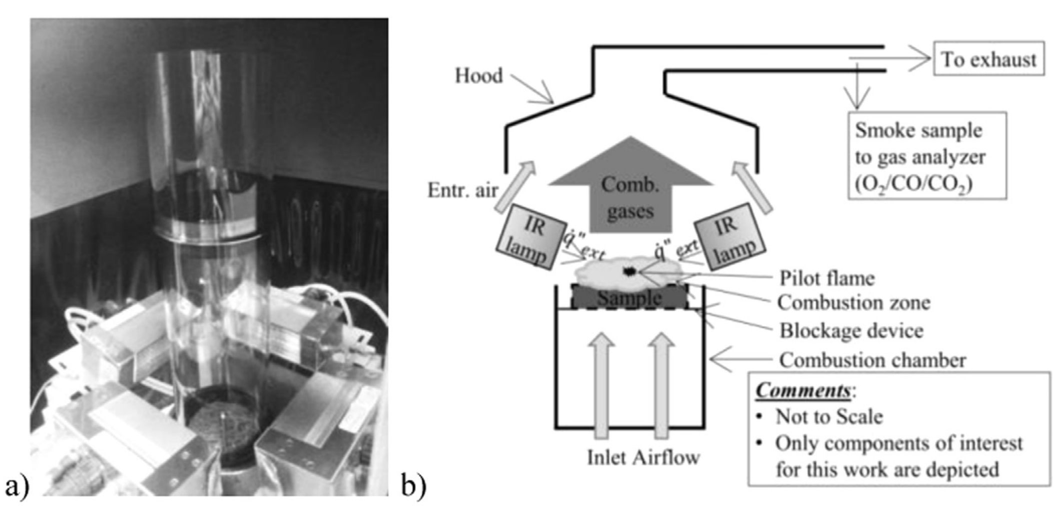


**Fig. 1.** (a) Photograph of the FPA test chamber with the quartz tube; (b) schematic of the FPA.