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EVALUATING FIRE EFFLUENTS DURING COMBUSTION OF WOOD BOARDS

Abstract: *Effluents generated during the flaming as well as non-flaming burning of materials may be regarded as the main cause of death and injuries from fires. The structure of fire gases highly depends on the physical condition and chemistry of fuel as well as burning conditions. During the combustion of organic materials, complex mixtures of fire gases may be created. This paper investigates fire effluent yields during the well-ventilated burning tests of lumber products – board samples from two common wood species: oak and fir. Experiments were performed in custom-designed laboratory installation hyphenating mass loss calorimeter (with chimney and thermopiles for heat release rate measurement) and FTIR gas analyzer for subsequent on-line analysis of evolved fire gases. Tests were conducted with two different heat fluxes: 30 and 40 kW/m². The focus was on continuous emission monitoring of three principal fire gas components: H_2O, CO_2, and CO with a particular emphasis on CO rates.*

Keywords: fire effluents, mass loss calorimeter, FTIR analysis, well-ventilated burning

INTRODUCTION

It is hard to find a building material that can outperform the benefits of wood. Wood construction products span from minimally processed lumber to engineered wood. It is usually a principal component found in the home furniture. However, wood materials are highly flammable and bring elevated fire hazards in enclosure spaces. During the wood-burning complex mixtures of fire, gases are created usually accompanied by soot. Primary components present in gaseous products of wood combustion are carbon monoxide, carbon dioxide, and water while the other gases/vapors may be present depending on the previous chemical treatment of wood/wood product [1].

Generally, the main toxic combustion products are divided into two classes: asphyxiant gases (gases that cause loss of consciousness and death), and irritant gases which cause immediate incapacitation. The most common toxic components of fire effluents are presented in Table 1 [2]. The yield and structure of fire gases highly depend on the physical state of fuel, its chemistry as well as burning conditions.

Table 1. *List of main asphyxiant and irritant gases*

Asphyxiant gases	Irritant gases	Other components
Carbon monoxide (CO) Hydrogen cyanide (HCN)	Hydrogen fluoride (HF) Hydrogen chloride (HCl) Hydrogen bromide (HBr) Nitrogen dioxide (NO₂) Sulphur dioxide (SO₂) Organic irritants	Oxygen (O₂) Carbon dioxide (CO₂)

The study of fire effluents attracted considerable attention in recent years. The most notable contribution was made through the EU-funded research program "Smoke Analysis by Fourier Transform Infrared spectroscopy (SAFIR)". Results of this project established Fourier-transform infrared spectroscopy (FTIR) as a method of choice in fire effluents research. FTIR is now routinely used in fire research [3].

In this study, a specially designed installation, containing a mass loss calorimeter and FTIR analyzer, was used for continual emission monitoring of fire effluents during the well-ventilated combustion of wood board samples (oak and fir). Tests were performed with two predefined heat fluxes: 30 and 40 kW/m² with piloted ignition. The focus of the analysis was on the three dominant components in the fire effluents: CO_2, H_2O, and CO. It was expected that the other species will be below or on the lower detection limit of the FTIR instrument. The objective was to determine the moments and appropriate levels of CO, the principal toxicant in most fires, during the tests.

EXPERIMENTAL SETUP

Mass loss calorimeter

Burning tests were performed on a mass loss calorimeter (MLC) (Fire Testing Technology, UK). Apparatus, containing fire model, chimney with thermopile (for heat release measurement), and load cell was placed in a custom-designed fume cupboard (Fig. 1). The exhaust system (hood, fan, and sampling ports) was manufactured according to recommendations from ISO 5660 [4]. MLC is routinely used for fast screening of materials fire characteristics.

This instrument contains the same fire model (truncate cone heater) as cone calorimeter and can produce heat fluxes up to 100 kW/m^2. In this study, MLC was used for measurement of heat release rate (HRR), total heat released (THR), mass loss rate (MLR), specific mass loss rate (SMLR), and effective heat of combustion (EHC). According to recommendations from ISO 5660, the volumetric flow rate was set to 0.024 m^3/s.

Figure 1. *Devices used in the experiment*

Fire gas analysis

On the horizontal run of the main exhaust pipe, 200mm before ventilator intake, a connection port for a probe for sampling fire effluents was made. The connection was made with treaded Swagelok fitting. For a continuous sampling of fire gases evolved during the combustion process specially designed probe was used (Figure 2). Fire effluent analysis was performed with FTIR gas analyzer DX-4000 (Gasmet, Finland). FTIR assembly contained three units: sample probe, pump, and gas analyzing cell. All three units were connected with a transport line, which was heated up to 180 ℃, to avoid water vapor condensation and trapping of water-soluble compounds.
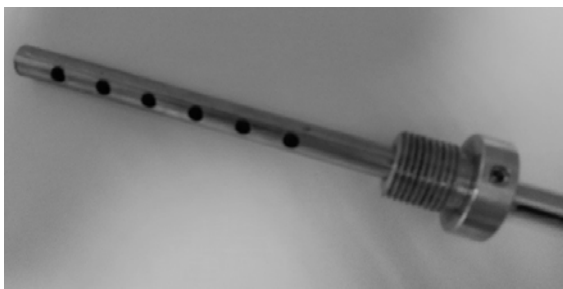

Figure 2. *Special design probe for analyzing exhaust gaseous*

FTIR analyzer enables the identification and quantification of several combustion product species: H_2O, CO_2, CO, N_2O, NO, NO_2, SO_2, NH_3, HCl, HF, CH_4, C_2H_6, C_2H_4, C_3H_8, C_6H_{14}, $CHOH$.

Samples studied

Two common lumber species oak and fir (to represent softwood and hardwood) were selected for combustion analysis. These species are often used in construction, manufacture, and as part of home furniture. The tested specimens were purchased from a local sawmill and cut to a standard dimension (100 mm x 100 mm) to accommodate a sample holder. The studied specimens were 21 mm thick with the following masses: oak sample – 135 g and fir sample – 86 g.

Tests were performed with a retainer frame, meaning that the only top side of the specimen was exposed to incident radiation from the conical heater. Quartz wool pads and ceramic boards were used to isolate the bottom of the sample from the sample holder. Before the test, specimens were wrapped with 0.05 mm thick aluminum foil. Distance between the sample surface and conical heater edge was set to standard 25 mm. Figure 3 presents prepared samples for the experiment.
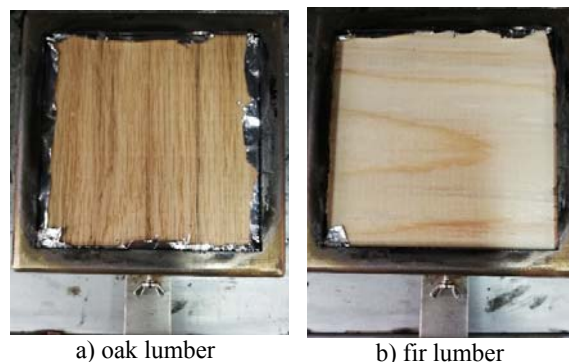

a) oak lumber   b) fir lumber

Figure 3. *Prepared samples in a sample holder*

Two prescribed heat fluxes were used during the experiments: 30 and 40 kW/m^2. Tests were performed with piloted ignition. For piloted ignition spark plug was used. The spark plug was positioned centrally above the specimen surface and kept until the flaming combustion commenced.

Calibration of equipment

Before the experiment started, the gas analyzer and MLC were calibrated.

Calibration of FTIR gas analyzer relies on reference spectra recorded on a computer and daily background spectrum measurement with zero gas (N_2) which compensates for any variation in the IR source and sample cell. To support this idea, FTIR gas analyzers do not require periodic recalibration. A daily background spectrum measurement with zero gas is enough to preserve measurement accuracy [5].

Calibration of MLC was performed in a few stages. It consists of calibration of conical heater against desired

heat flux (with Schmidt-Boelter heat flux meter), chimney thermopile for heat release rate measurement (calibration with methane burner), and load cell calibration for anticipated masses of specimens.

RESULTS AND DISCUSSION

Figures 4 and 5 show the measured emissions of the fire effluents which were generated during the combustion process, at a specific heat flux of 30 and 40 kW/m². Volumetric concentrations of the following species were measured: H_2O, CO_2, CO, and CH_4. Concentrations are presented along with the evolution of the mass-loss rate (MLR). Note that MLR values on the left graphs in figures 4 and 5 are shown on the right vertical axis, while on the right graphs in figures 4 and 5 mass-loss rates are presented as MLR*1000, to provide better insight into obtained results and facilitate comparison with concentration levels.

While FTIR instrument additionally measures the content of the following species: N_2O, NO, NO_2, SO_2, NH_3, HCl, HF, C_2H_6, C_2H_4, C_3H_8, $C_6H_{14,}$ and CHOH, values are not presented and further discussed because detected concentrations during the experiments were very low i.e. under 10 ppm.

Ignition time and moment of flameout are marked, with vertical lines and appropriately designated. Table 2 shows the exact times for IT and FOT, for both incident heat fluxes. Ignition and flameout times are shorter for higher heat fluxes as was expected. The difference is less pronounced for times to ignition than for flameout times. Moreover, the difference between flameout times for two incident fluxes is more obvious for fir than for oak.

Table 2. *Ignition time and flame-out time for analyzed samples*

Sample name	30 kW/m²		40 kW/m²	
	IT (s)	FOT (s)	IT (s)	FOT (s)
Oak tree	83	1737	30	1433
Pine tree	55	1252	16	1199

For both wood samples, CO_2 and H_2O were dominant species detected, with water being the most prominent product. Concentration profiles of these two species (H_2O and CO_2) have a major contribution to the shape of the mass-loss rate (MLR) curve profile. One part of the water in fire gases originates from the evaporation of "free" and "linked" water. "Free" water pertains to water absorbed by organic material, while "linked" water refers to water bound to original material through weak hydrogen bonds. The other part is water vapor created from hydrogen content in the fuel.

As shown in Figure 4, for the oak sample, the CO_2 concentration profile, has two distinct peaks, regardless of the value of incident heat flux. The first peak corresponds to CO_2 emitted during the ignition of the sample. The second peak corresponds to the moment when the specimen starts swelling up, allowing the oxygen to penetrate from previously enclosed sides. Unlike oak sample, fir has only one peak of CO_2 concentrations, which occur after the ignition of the sample (Figure 5). This finding is valid for both heat flux, 30 and 40 kW/m². Measured concentrations of CO_2 for oak samples were somewhat lower when compared to fir samples.

As to the CO emission, higher concentrations were noticed for lower heat fluxes. After the ignition, CO concentrations start rising. It seems that despite the well-ventilated conditions, oxygen diffusion in flame was not sufficient. CO concentration reaches the first peak in the period between the ignition time (IT) and flameout time (FOT). Near the second MLR peak CO concentration start to decrease. This moment corresponds to the point when the sample is fully engulfed in flame and starts to burn through the whole volume. For some time oxygen unimpededly diffused in flame, enabling complete combustion, and this corresponds to a minute concentration of CO. After the second MLR peak, the concentration of pyrolyzed gases above the surface of the fuel in the mixture with air were below the flammability limit, and the flame ceased. After the flameout, a high increase of CO concentration was noticed, which indicates the second, the higher peak of CO. Oak lumber gives the highest values for both heat fluxes. In the case of fir lumber, for both heat fluxes, CO concentrations had about the same trend.

In the case of CH_4 concentration, for all samples, in the period between IT and FOT, there were no significant released concentrations. From the beginning of the experiment, any increase or decrease in concentrations has not been noticeable. The first and only peak value was noticed in the period after FOT. During smoldering, CH_4 concentration starts to rise. This observation holds for both samples.
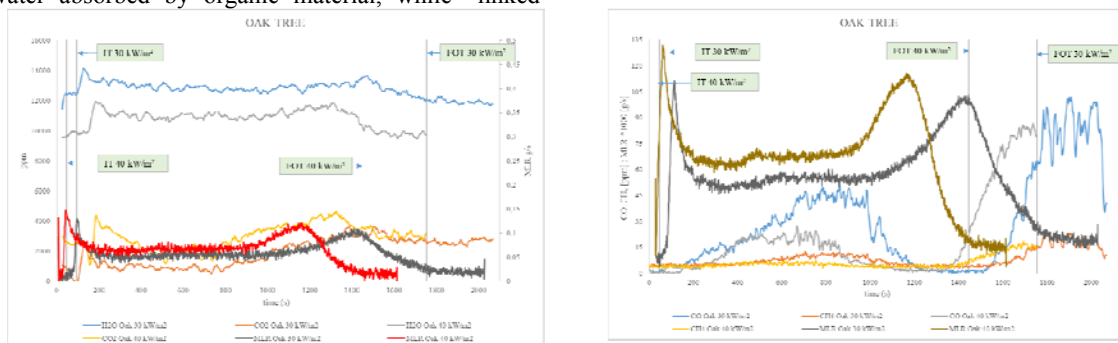

Figure 4. Evolution of fire effluents during the oak sample burning test for two incident heat fluxes: 30 and 40 kW/m²
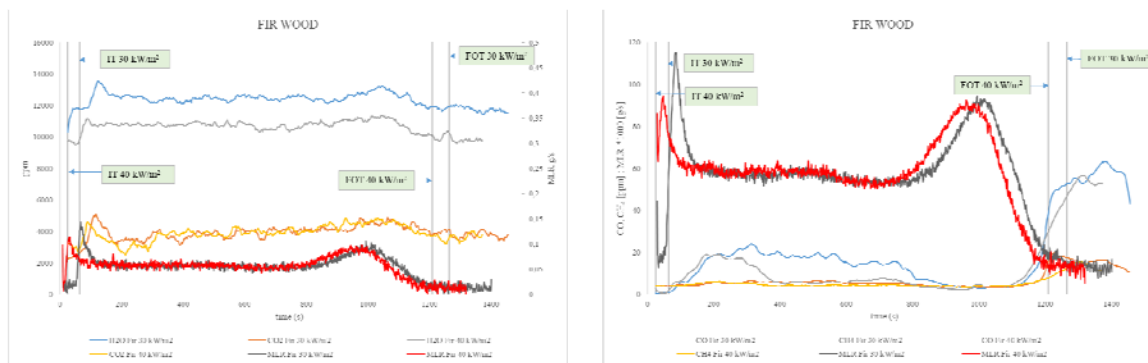
Figure 5. Evolution of fire effluents during the fir sample burning test for two incident heat fluxes: 30 and 40 kW/m²

CONCLUSION

In this study, a mass loss calorimeter was coupled with an FTIR gas analyzer to investigate fire effluents from the most commonly used wood types.

Based on the analysis, the following concluding remarks can be drawn:

- H_2O and CO_2 were the two dominant species present in the flue gases;
- CO_2 concentrations were heat flux dependent for oak lumber, while for fir lumber significant difference was not detected;
- CO emission had a characteristic two-peak profile for both samples, regardless of incident heat flux, with more distinct shape for oak lumber sample;
- While CH_4 concentration was minute almost during the whole course of the experiment, values started to rise immediately after flameout.

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BIOGRAPHY of the first author

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ODREĐIVANJE EFLUENATA POŽARA PRI SAGOREVANJU DRVENIH PLOČA
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Rezime: Generisanje efluenata požara pri plamenom i tinjajućem sagorevanju materijala, mogu biti glavni uzroci smrti i povreda usled požara. Struktura gasova u požaru u velikoj meri zavisi od fizičkog stanja i hemijskog sastava goriva kao i uslova sagorevanja. U toku sagorevanja organskih materijala, mogu se stvoriti složene smeše gasova. Ovaj rad istražuje efluente požara u dobro ventilisanim uslovima sagorevanja proizvoda od drveta - uzorci ploča dveju uobičajenih vrsta drveta: hrasta i jele. Eksperimenti su izvedeni u specijalno projektovanoj laboratoriji na kalorimetru za ispitivanje toplotne snage (sa dimnjakom i termoparovima za merenje toplotne snage) i FTIR gasnim analizatorom za analizu nastalih gasova u požaru. Ispitivanja su vršena za dva različita toplotna fluksa: 30 i 40 kW/m². Fokus je bio na kontinuiranom praćenju emisija tri glavne komponente gasova u požaru: H_2O, CO_2 i CO sa posebnim naglaskom na CO.

Ključne reči: efluenti požara, kalorimetar za ispitivanje toplotne snage, FTIR analiza, ventilisano sagorevanje.