

Characterization of Toxic Gases and Particulates in Wood Smoke using a Standard Chamber

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ABSTRACT

Smoke inhalation is a major cause of civilian and firefighter deaths during a fire incident. To characterize effluents from burning or pyrolyzing wood, real-time measurements of the smoke obscurity (the specific optical density), the concentrations of particulates, and toxic gases in a standard smoke density chamber have been made with a tapered element oscillating microbalance (TEOM) dust monitor and a Fourier transform infrared (FTIR) gas analyzer. The FTIR analyzes a total of 21 gases, including both asphyxiants and irritants. In addition to the smoke characteristics, the temperature in the interior of the specimen under selected conditions are measured by thermocouples to study the heat transfer and pyrolysis processes. Common building materials, i.e., selected woods at various moisture contents, are used. A specimen, placed in a vertical or horizontal orientation, is exposed to an incident radiant flux of 25 kW/m² for a flaming or non-flaming case. The effluent concentrations depend significantly on whether or not the flame exists and the specimen orientation as they influence the gas-phase reactions and the convection around the specimen. The non-flaming case in the horizontal configuration produces the highest smoke and toxicants (CO, formaldehyde, and acrolein) concentrations due to partial oxidation, while the flaming and horizontal case generates the lowest because of high-temperature oxidation (to form CO₂ and H₂O) in a flame with a longer residence time.

KEYWORDS: Fire toxicity, smoke obscurity, wood pyrolysis, moisture content, carbon monoxide, acrolein, formaldehyde

INTRODUCTION

Between 2011 and 2015, the U.S. fire departments responded to an average of 358,500 home structure fires per year, which, caused an average of 2,510 civilian deaths annually [1]. Many of these deaths were caused by smoke inhalation, where hot smoke injured or burned the respiratory system [1] or toxic gases exceed the exposure limits. Certain gases only require small concentrations for them to be lethal to the victims [2, 3].

Fire responders are often at a greater risk of inhaling toxic gases during the cleanup phase after a fire when they remove the self-contained breathing apparatus (SCBA) or replace with lesser personal protection equipment (PPE). Table 1 shows a limited list of occupational exposure limit standards of selected toxicants, which have been detected in excess concentrations during the post-fire (overhaul) period. Firefighters' safety officer often uses a detector of a major asphyxiant gas, i.e., carbon monoxide (CO), to make sure the environment is safe for them to enter, as gas masks can only filter out some particulates and toxic gases [4]. For example, when they are in open area zone with no visible fire (but possibly smoldering), they can use CO detectors to ensure that the concentration is not lethal [4, 5], e.g., less than 35 ppm. This value corresponds to the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) and

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much lower than the immediately dangerous to life or health (IDLH) concentration. However, it would be possible that other toxicants, e.g., hydrogen cyanide (HCN), and ultrafine particles (< 100 nm) exist in significant concentrations. Nevertheless, there are no commercially available hand-held devices that can detect both particulates and traces of toxic gases, and development of such device is currently underway [7].

Hence, irritants (e.g., formaldehyde and acrolein) are particularly important as they often incapacitate so quickly that people cannot make it to an exit. Due to their highly toxic nature, NIOSH REL and IDLH concentrations of formaldehyde (CH₂O) or acrolein (C₃H₄O) are very low [6, 7].

Table 1. Exposure standards of selected toxicants

Chemical	Formula	NIOSH REL ^a	IDLH ^b
Carbon Monoxide	CO	35 ppm	1200 ppm
Hydrogen Cyanide	HCN	4.7 ppm	50 ppm
Formaldehyde	CH ₂ O	0.016 ppm	20 ppm
Acrolein	C ₃ H ₄ O	0.1 ppm	2 ppm
Benzene	C ₆ H ₆	0.1 ppm	500 ppm

^aNational Institute for Occupational Safety and Health, recommended exposure limit.

^bImmediately dangerous to life or health.

Formaldehyde is a highly reactive aldehyde gas formed by oxidation or incomplete combustion of hydrocarbons [6]. Direct skin contact to formaldehyde at 100 ppm causes a severe reaction. It can be readily absorbed when inhaled and can cause headaches and respiratory issues from 0.5 ppm [8, 9]. Acrolein is a strong irritant to skin and mucous membranes. It is also extremely toxic if inhaled or ingested, and still dangerous with skin contact [7]. The occupational exposure limits in the short-term exposure limit (STEL) is 0.1 ppm [10, 11]. In addition to these acute effects, chronic effects (e.g., cancer) can result from accumulated damage from multiple exposures for firefighters. Formaldehyde and benzene are known carcinogens.

The objectives of this study are: (1) to determine the types and concentrations of various toxicants in fire smoke from common building materials; (2) to gain a greater understanding of smoke toxicant generation processes, including pyrolysis, off-gassing, and burning; and (3) to assist in the development of particulates and toxic gas detectors for fire responders.

EXPERIMENTAL METHODS

Apparatus

A standard smoke density chamber (SDC, Fire Testing Technology [FTT]) is used with the capability of a Fourier transform infrared (FTIR) gas analyzer (Protea atmosFIR AFS-A-15) and a tapered element oscillating microbalance (TEOM) personal dust monitor (Thermo Environmental Instruments, PDM 3700).

The SDC provides a safe isolated environment (0.914 m width × 0.610 m depth × 0.914 m height) and consists of a radiant cone heater, a specimen holder, and a smoke obscuration measurement system, including a vertically upward light source and a photo detector. The radiant heat flux can be directed horizontally with a vertical fuel surface (ASTM E266) or vertically with a horizontal surface (ISO 5659). The specific optical density (SOD or D_s), i.e., a measurement characteristic of the concentration of smoke, is calculated, while the light beam is obscured by the smoke generated by the fuel, as follows:

$$D_s = V/(AL) \times \log(100/T), \quad (1)$$

where V = chamber volume (0.510 m^3), A = exposed specimen area (0.0043 m^2), and L = light path length (0.914 m), and T = actual light transmission (relative intensity, %).

The FTIR gas analyzer and the TEOM dust monitor are connected to gas-sampling tubes (stainless steel, 5 mm i.d., 30 cm length) installed inside the SDC through the sampling ports near the center of the top wall. Gases are extracted at fixed sampling rates from each sampling port (FTIR: 1.5 lpm, TEOM: 2.2 lpm), and once analyzed, are returned to the chamber through another port near the sampling ports to prevent a vacuum pressure. The sampling line between the SDC and FTIR is maintained at $180 \text{ }^\circ\text{C}$ to prevent species condensation.

The FTIR has a multi-pass gas cell operating at $180 \text{ }^\circ\text{C}$ with the path length set as 4.2 m and the spectral resolution of the interferometer set to 4 cm^{-1} . The FTIR gas analyzer distinguishes 21 unique compounds from a library, including gases of interest in the present study: combustion products (H_2O , and CO_2) asphyxiant gases (CO and HCN), sensory irritant gases (formaldehyde and acrolein). The FTIR is calibrated for each species in the following ranges: H_2O (0-30.14%), CO_2 (0-2.47 %), CO (0-98.72 ppm), HCN (0-606 ppm), HCHO (0-16.5 ppm), and $\text{C}_3\text{H}_4\text{O}$ (0-431 ppm). To prevent contamination from previous test runs, the FTIR is purged with N_2 (99.999 %) and checked daily with a standard gas mixture (0.85 % CO and 8.5 % CO_2). The data acquisition rate is typically 1/4 Hz.

The TEOM dust monitor is typically used by coal miners to take direct measurements of particulate mass concentration. Particulates are collected on a filter and their mass is measured by a tapered element oscillating microbalance in real time. The data acquisition rate is 1/60 Hz.

All experiments (except for the specimen temperature measurement to be described) are run in accordance to ASTM E662 (with a horizontal incident heat flux, q , of 25 kW/m^2 on a vertical specimen surface) or ISO 5659 (vertically downward heat flux on a horizontal specimen). For the ASTM flaming test, a pilot flamelet burner is placed between the horizontal heating furnace and the specimen to introduce pilot flames. Multiple pilot flames are set to have contact with the sample as soon as the test begins. To achieve the proper flame length, the average propane and air flow rates are around 70 ccm and 550 ccm, respectively. For the ISO vertical cone flaming test, a single pilot flame, about 30 mm in length, is oriented from the side, such that the tip of the flame is approximately in the center of the sample. To achieve proper flame length, the average propane and air flow rates are around 50 ccm and 300 ccm, respectively. It is possible that CO and CO_2 from the pilot flame could affect the total readings from the chamber. Thus, the apparatus has been tested without a specimen for gas emissions of the pilot flame. The concentrations of CO and CO_2 produced from said pilot flame is near negligible in comparison to those produced from the burning specimen.

The standards used are made to test for building materials and textiles on a bench scale. There are limitations of any bench-scale testing of materials when applying findings to a large-scale testing or a real fire where the imposed incident heat flux may vary with time. The present approach does not attempt to simulate the larger-scale standard fire resistance test or compartment fire conditions. Unlike some other tests such as the cone calorimeter with a vitiation chamber, in which incoming air flow rate is controlled, there is no such combustion condition like the fuel:air equivalence ratio exists in the overventilated smoke density chamber test. The toxic product yields have been determined but not reported here as the results depend on the location where the gases are sampled.

Specimen preparation

Each specimen is cut to $75 \pm 1 \text{ mm}$ by $75 \pm 1 \text{ mm}$ and planed to the thickness $L = 12.7 \pm 0.2 \text{ mm}$, and prepared by drying them in a forced-convection oven at $103 \pm 2 \text{ }^\circ\text{C}$ for at least 24 hours to get a

base mass. Then, they are submerged in distilled water under a controlled environment for an extended period until the desired moisture content is achieved.

The moisture content of the wood is calculated by the following [12]:

$$MC = (A - B)/B \times 100 \%, \quad (2)$$

where A = original mass (g) and B = oven-dry mass (g). For selected wood specimens for the ISO 5659 setup, interior temperatures are measured by five K-type thermocouples (TCs) at incremented depths from the initial top surface of the specimens. The thermocouples (labeled by numbers in Figure 1) are placed at the following coordinates, depth (y) and radius (r) in mm; No. 1: (0, 0), Nos. 2 and 4: (6.35, 10), No. 3: (9.53, 10), No. 5: (12.7, 10). In addition to the five TCs in the specimen, two TCs are placed nearby the inlet of the sampling tube and the chamber floor.

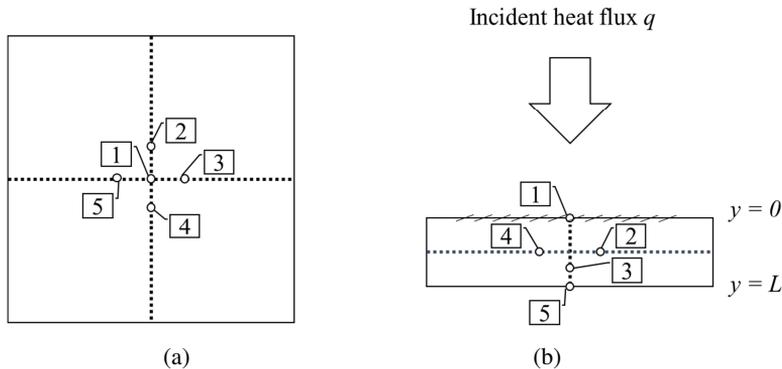


Fig. 1. Thermocouple set up in a specimen oriented horizontally (with a vertical radiant flux from the cone heater). (a) top view; (b) cross-section view.

RESULTS AND DISCUSSION

Vertical specimen configuration

Under the vertical specimen configuration (ASTM E662), the effects of the type of wood (species including softwood—pine and cedar, and hardwood—oak) and the moisture content are studied in the flaming and non-flaming cases. Tables 2 and 3 summarize the results for the flaming and non-flaming cases, respectively. For each sample, the mass loss (%), the maximum specific optical density (Ds), the ignition time, and the concentrations of selected species, i.e., H_2O , CO_2 , CO , formaldehyde, and acrolein, are listed.

For both flaming and non-flaming cases, the mass loss at the end of experiment (the elapse time: between 10-15min for flaming and around 18-20min for non-flaming) generally decreases with the moisture content. It is expected that there is a decrease in the mass loss, i.e., an increase in the residual wood material (and moisture), because more heat is required to raise the temperature of the material with increased total heat capacity from water and to vaporize the water, i.e., the heat of vaporization.

This is also reflected in the ignition times for the flaming tests; that is, the more moisture a sample contains the longer it takes to ignite. Oak also experiences less mass loss and much longer ignition time since it is denser and has larger heat capacities than the other two types of wood.

For the flaming test, all the specimens ignite, leading to vigorous burning, and produce less smoke (lower max. Ds), compared to the non-flaming tests. There is less consistency in the flaming test for Ds and MC correlation. It is known that for a complete combustion, CO_2 and H_2O are formed,

whereas for an incomplete combustion or pyrolysis, more CO is produced. Thus, Tables 2 and 3 show that the concentrations of CO₂ and H₂O are generally higher and that of CO is generally lower in the flaming test compared to the non-flaming. When the wood is ignited, a charring process will occur and continue to propagate within the wood. Wood with higher MC require more energy due to the heat of vaporization and higher specific heat, leading to a delay in the charring process. The efficiency of the combustion is reduced, thus increasing by-products of incomplete combustion such as CO and smoke. If there is no ignition, it is probable that the moisture is protecting the interior of sample from pyrolysis. Therefore, less MC wood is more likely to produce complete combustion products, leading to less smoke and aerosol (steam).

Table 2. Characteristics of smoke from flaming vertical woods at various moisture contents

Wood Type	MC (%)	Mass loss (%)	Max Ds ^a	Ignition (s)	H ₂ O (%)	CO ₂ (%)	CO (ppm)	Formaldehyde (ppm)	Acrolein (ppm)
Pine	0	39.8	105	2	2.74	1.61	711	37.3	3.9
Pine	20	38.7	61	3	2.95	1.41	670	28.3	3.1
Pine	40	36.3	142	7	2.99	1.09	853	42.5	6.1
Cedar	0	51.3	131	3	3.58	2.18	1600	95.3	5.9
Cedar	20	44.7	153	5	3.33	1.21	1020	73.6	7.6
Cedar	40	36.7	21	9	3.04	1.05	825	39.2	2.5
Oak	0	40.8	70	19	3.06	2.18	286	43.0	9.5
Oak	20	34.2	142	23	4.67	1.97	911	52.1	10.5
Oak	40	31.9	250	29	4.66	1.32	858	51.9	8.4

^aDs values after 10 minutes of exposure – for flaming tests, there is no “peak”, and Ds increases until end of test

Table 3. Characteristics of smoke from non-flaming vertical woods at various moisture contents

Wood Type	MC (%)	Mass loss (%)	Max Ds	Density (g/cm ³) ^a	H ₂ O (%)	CO ₂ (%)	CO (ppm)	Formaldehyde (ppm)	Acrolein (ppm)
Pine	0	47.0	413	0.33	1.56	0.72	4300	95.9	8.2
Pine	20	43.4	337	0.38	2.32	0.35	2213	75.9	3.7
Pine	40	42.2	351	0.44	2.55	0.32	1965	66.8	3.3
Cedar	0	45.8	452	0.34	1.59	0.64	2766	116.2	1.4
Cedar	20	45.2	296	0.40	3.02	0.48	2167	94.1	0.8
Cedar	40	36.4	227	0.47	2.91	0.27	907	63.0	0.8
Oak	0	25.6	530	0.71	1.86	0.33	1614	68.2	7.3
Oak	20	21.6	118	0.87	3.15	0.12	162	35.3	1.3
Oak	40	22.9	74.6	0.99	3.59	0.10	108	27.8	3.5

^aAverage between same wood type and MC – same values for flaming condition.

The concentrations of formaldehyde and acrolein exhibit, to some extent, opposite trend between flaming and non-flaming cases. The concentration of formaldehyde is generally lower (except oak, MC: 20 and 40 %) and that of acrolein (except pine, MC: 0 and 20 %) is generally higher in flaming than non-flaming. As these species are intermediates in the high-temperature gas-phase oxidation processes, the higher temperature in the flaming case may be a factor affecting the differences.

In the non-flaming case, smoke would contain aerosols of condensed water vapor and/or thermally degraded fuel pyrolyzates. Both formaldehyde and acrolein are water soluble. As such, both species can be dissolved in aerosol particles and conveyed as vaporized gases through the heated line to the FTIR gas analyzer. This may also hold for the flaming test for higher moisture contents, in which less fully burned fuel is observed.

Effects of specimen orientation

Because of the Earth gravity, the orientation of the specimen surface; i.e., vertical (ASTM E662) and horizontal (ISO 5659), affects the results significantly. In the vertical orientation, the pilot flame is directly facing the specimen, and the convective forces and buoyancy from the flame runs parallelly with the surface of the specimen. In the horizontal orientation, the pilot flame is parallel to the specimen surface, and the convective forces and buoyancy is perpendicular to the specimen surface. Therefore, the heat transfer throughout the sample is influenced. This situation relates to a difference between a wall burning and the floor burning.

Table 4 shows a summary of the effects of the specimen orientation for pine with 0 % MC in the flaming and non-flaming cases. The measurement data for the first 20 min are recorded. No auto-ignition occurs without a pilot flame, while the piloted ignition takes place within the first few seconds for both orientations. The experiment is repeated three times for consistency with results. As is already described for the vertical orientation in the preceding section, for the horizontal as well, there is more CO₂ and H₂O, while there is less smoke and CO in the flaming case. The non-flaming case, particularly in the horizontal configuration, produces the highest smoke and toxicants (CO, formaldehyde, and acrolein) concentrations due to partial oxidation, while the flaming and horizontal case generates the lowest because of high-temperature oxidation (to form CO₂ and H₂O) in a flame with a longer residence time.

Table 4. Effects of specimen orientation for dry pine under the flaming and non-flameing conditions

Specimen Orientation	Flaming Condition ^a	Mass Loss (%) ^b	Max. Ds	H ₂ O (%) ^b	CO ₂ (%) ^b	CO (ppm) ^b	Formaldehyde (ppm) ^b	Acrolein (ppm) ^b
Vertical	NF	53.13	413	1.56	0.72	4300	95.9	8.2
Vertical	F	54.04	208	3.81	2.32	2326	56.3	11.0
Horizontal	NF	56.76	570	2.82	0.84	4757	164.4	13.2
Horizontal	F	64.18	90	4.01	3.64	638	21.7	4.1

^aNF: non-flaming, F: flaming

^bAfter 20 minutes of heat exposure

Figure 2 shows the temporal variations of the specific optical density and the particulate mass concentration. In Fig. 2a, note that for both vertical and horizontal orientations, the smoke density is much less with the flaming condition. For the flaming case, the vertical orientation produces much more smoke in comparison to the horizontal orientation. There is more than double the Ds value of horizontal observed in the vertical orientation by the end of the 20 minutes.

For the non-flaming condition, the horizontal orientation has more smoke than vertical orientation. The Ds for non-flaming tapers off after reaching a maximum value, which results in the Ds' to have a greater difference at the end of test. The vertical Ds does not taper off as much horizontal orientation, and appears to plateau.

Figure 2b shows a striking difference; the mass concentration of particulates in the non-flaming case has large peaks, whereas that in the flaming case is very low. Unlike Ds, which is a line-of-sight measurement, the the mass concentration is measured for the gas sampled at fixed location in the

chamber (≈ 30 cm below, i.e., $\approx 1/3$ of the chamber height, near the center of the top wall surface). Thus, measured mass concentration becomes zero if particles do not enter the sampling tube inlet. Mass loss rate for the flaming and non-flaming is different in horizontal orientation, but not too different in vertical orientation. It is likely that the convection from the pilot flame in the vertical orientation in flaming facilitated the mass loss in a similar fashion for non-flaming case.

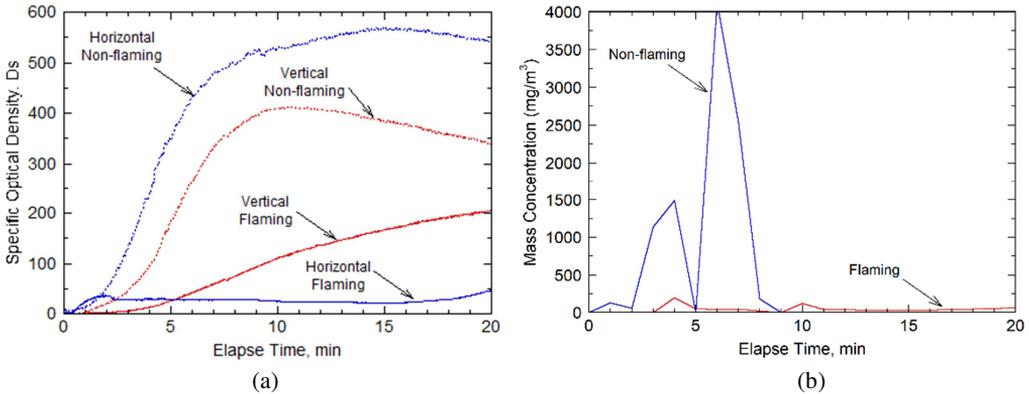


Fig. 2. Temporal variations of (a) the specific optical density (vertical and horizontal specimen) and (b) the particulate mass concentration (horizontal specimen).

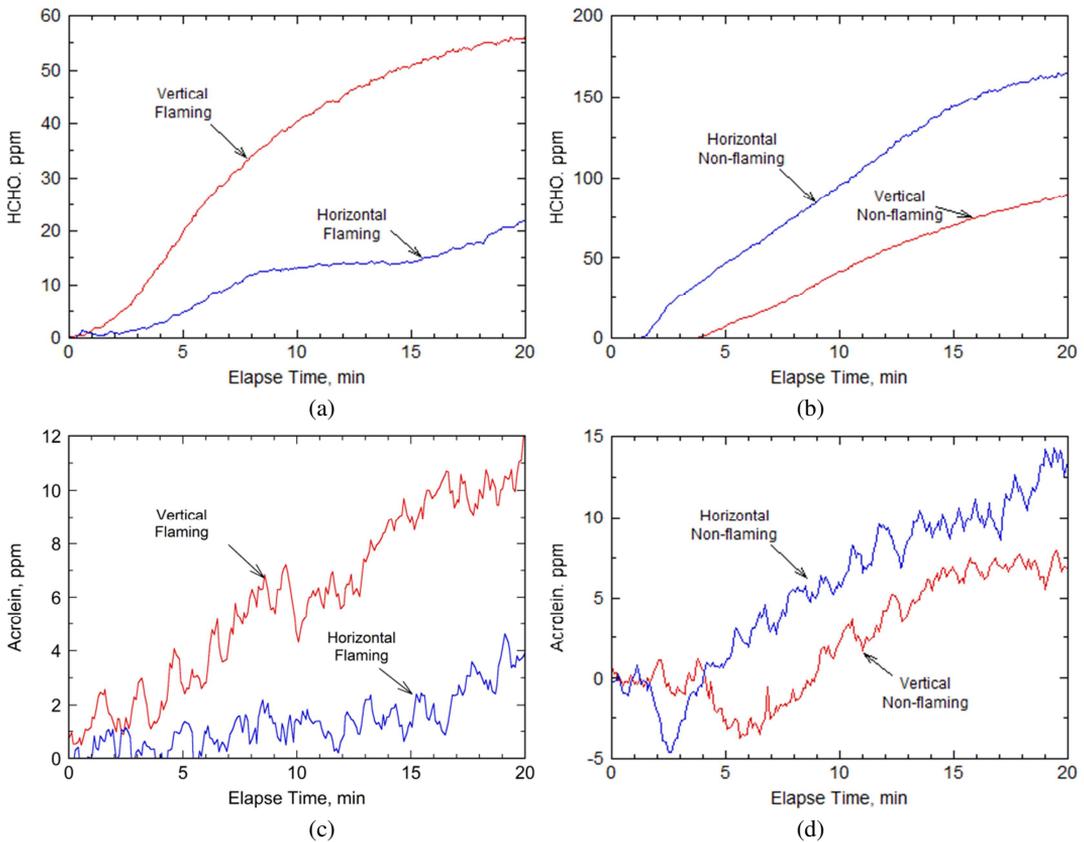


Fig. 3. Temporal variations of (a, b) formaldehyde and (c, d) acrolein concentrations. (a, c) Flaming and (b, d) non-flaming cases. Negative values indicate concentrations are too low for FTIR to read accurately.

Figure 3 shows the temporal variations of (a, b) formaldehyde and (c, d) acrolein concentrations in (a, c) flaming and (b, d) non-flaming cases. For both vertical and horizontal specimen orientation, the concentrations of both formaldehyde and acrolein are generally higher in the non-flaming case than in the flaming case. However, the measured concentration of formaldehyde largely exceeds its maximum calibration range (16.5 ppm) and that of acrolein is small (< 3.5 % of full scale). As a result, quantitative values of these measurements less reliable than a stated accuracy of 2% with respect to the actual values. Nevertheless, the differences between the flaming and non-flaming as well as the vertical and horizontal specimen surface seem to be significant.

For the flaming cases (Fig. 3a and 3c), the concentration of both formaldehyde and acrolein are much higher in the vertical specimen orientation than the horizontal. This correlates with the max Ds for vertical orientation being much higher than the horizontal orientation. As described for Table 4, the flaming and horizontal case generates the lowest because of high-temperature oxidation (to form CO₂ and H₂O) in a flame with a longer residence time, whereas the vertical case induces natural convection along the specimen and reduce the residence time.

For non-flaming cases (Fig. 3b and 3d), the trend is opposite; the concentration of both formaldehyde and acrolein are higher in the horizontal specimen orientation than the vertical. Here, the maximum Ds for horizontal orientation is higher, indicating more irritants are produced in the wood smoke.

Specimen temperature

Figures 4 shows the temporal variations in the measured temperature in the interior of the horizontally orientated specimen (pine at 0% MC, 12.7 mm thickness) in (a) flaming and (b) non-flaming. For both flaming and non-flaming cases, the temperatures in the depth of 6.35-12.7 mm (TC2 – TC5) exhibit a consistent decreases in their slopes to a steady, almost linear slope at ≈12 min. The slopes appear to be quite similar, indicating that the specimen is experiencing the similar processes. For the flaming case (Fig. 4a), at 15 min, the thermocouple at the depth of 0 mm (TC1), which is exposed as the surface regresses, exhibit a sudden decrease, most likely reflecting a change in the flame condition. For the non-flaming case (Fig. 4a), the temperature at 0 mm reaches its maximum (≈600 °C) at 17 min more gradually.

The back of the specimen is ceramic wool with lots of air in void spaces, so it is intended to be insulated. Since the temperature gradient in the direction parallel to the specimen surface must be negligible, compared to that in the perpendicular direction (as shown in Fig. 4), the heat loss to the stainless steel sample holder in the periphery of the specimen must be negligible.

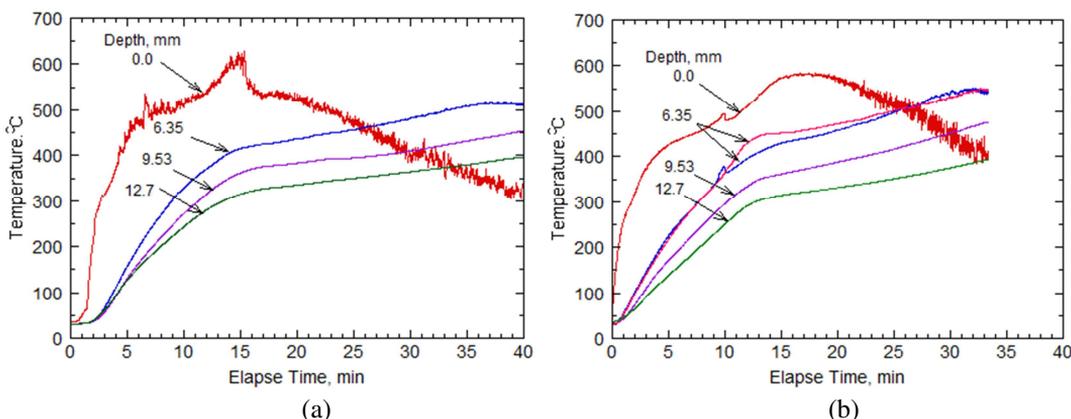


Fig. 4. Temporal variations of the temperature in the interior of the horizontally orientated specimen. (a) Flaming and (b) Non-flaming.

Figure 5 shows spatial variations in the measured temperature in the interior of the horizontally orientated specimen in (a) flaming and (b) non-flaming. For both flaming and non-flaming cases, by absorbing the incident heat, the surface temperature increases first, and resulting temperature gradient causes heat conduction to the specimen interior, thereby increasing the internal temperature. At ≈ 12 min, the thermocouple at the bottom of the specimen at the depth of 12.7 mm (TC5) reaches ≈ 290 °C.

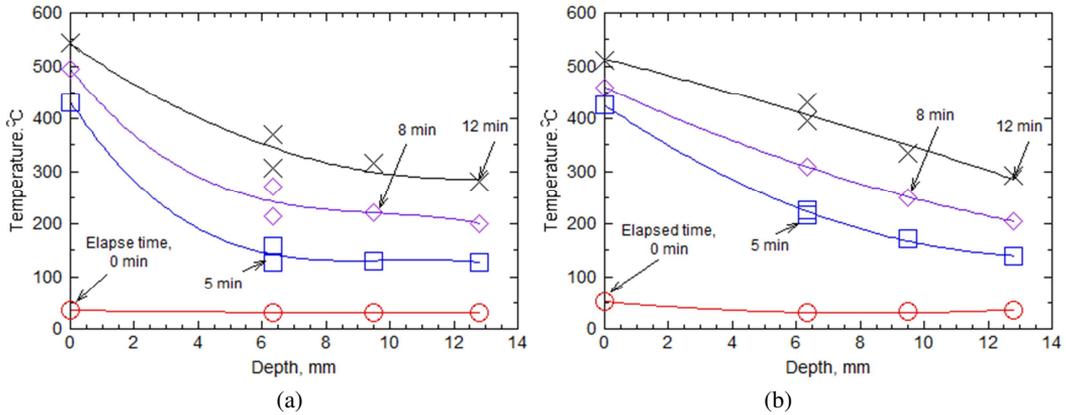


Fig. 5. Temperature in the interior of the horizontally orientated specimen. (a) Flaming and (b) Non-flaming.

The thermal degradation processes of wood are well understood [12]. Wood dehydrates and generates water vapor, CO₂, formic acid, acetic acid, and H₂O between 100 and 200 °C . Between 200 and 300 °C , significant amounts of CO are produced as a result of significant pyrolysis within some parts of the wood. Around 300 to 350 °C, cellulose begins to show significant depolymerization, Once the temperature reaches around 450 °C, which is the peak at which lignin degrades, the wood sample will cease volatile emissions.

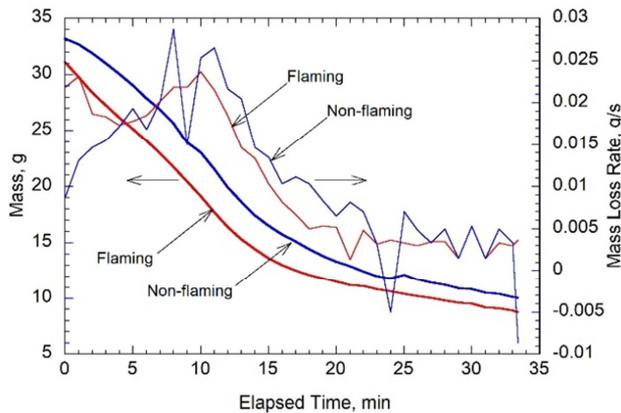


Fig. 6. Specimen mass and mass loss rate for flaming and non-flaming cases. The mass is presented at 1Hz, and mass loss rate is shown at 1/60Hz due to load cell sensitivity.

Since temporal variations of the temperature are similar for flaming and non-flaming cases (Fig. 4), thermal degradation processes must be similar as well. In the first 5 min, the specimen temperature becomes > 100 °C in every depth (Figs. 5a and 5b). At 8 min, the temperature increases to 200 – 300 °C. At 12 min, $> \approx 300$ °C and thus, the charring front reaches the back side of the specimen.. At slightly before 15 minutes, around 300 to 350 °C in the back side of the specimen, Afterwards, the

sample is simply being heated up at a constant rate (Fig. 4). Anything above 450 °C is mostly char, and as observed during the test, there is a thin layer of ashes covering the charred sample. Thus, the charring front must reach the back side of the specimen.

The advantages of using ISO 5659 (horizontal orientation) is that it provides mass loss data. Figure 6 shows the specimen mass and mass loss rate for flaming and non-flaming cases. The mass is presented at 1Hz, and mass loss rate is shown at 1/60Hz due to the sensitivity of the load cell.

The mass loss rate does not appear to be significantly different between flaming and non-flaming cases at first glance, except for the initial flaring (< 4 min) for the flaming case. This is specifically for 0% MC pine, and data shown is representative of the all flaming and non-flaming tests conducted with the same conditioned specimen.

CONCLUSION

Fire toxicity of wood smoke has been studied under flaming and non-flaming heating conditions using selected woods with various moisture contents, placed vertically or horizontally in the standard smoke density chamber with analytical instruments: a FTIR gas analyzer and a TEOM dust monitor. The conclusion can be summarized as follows.

1. The type of wood and the moisture content affect the pyrolysis, burning processes, and in turn, the toxic effluent emission through the variations in the fuel density and specific heat. A hardwood (oak) has a density about twice as large as soft woods (pine and cedar) and, in turn, a larger specific heat. As a result, oak takes a longer ignition delay time and generates less CO. Higher moisture content results in larger density and specific heat due to increase in mass and water within the specimen, thus requiring more energy to heat up the wood and leading to delay in charring. This reduces the efficiency of combustion, which leads to more smoke (higher Ds), and more toxic incomplete combustion products (CO, formaldehyde).
2. The effluent concentrations depend significantly on whether or not the flame exists and the specimen orientation as they influence the gas-phase reactions and the natural convection due to buoyancy around the specimen. The non-flaming case, particularly in the horizontal configuration, produces the highest smoke and toxicants (Ds, CO, formaldehyde, and acrolein) concentrations due to partial oxidation, while the flaming and horizontal case generates the lowest because of high-temperature oxidation (to form CO₂ and H₂O) in a flame with a longer residence time.
3. For both flaming and non-flaming cases, the heat exposure increases the specimen interior temperature rapidly until the pyrolysis and charring front reaches the back side of the specimen and the mass loss rate (or the fuel consumption rate) peaks out (around the elapse time of 12-15 min). As a result of charring of the entire specimen, the increasing rate of the specimen temperature decreased to a steady condition.

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