Thermal and Chemical Identification of Materials Prior to Combustion

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Abstract— The ability to identify, via remote sensing, the identity of materials prior to self-ignition is important for fire safety. We have developed a system to monitor, in real time, the thermal and chemical properties of specific materials under well controlled heating conditions. Our goal is to develop a library of the pre-combustion "signature" of materials commonly present in buildings. These signatures focus on the gases produced by combustion: CO, CO_2 and total hydrocarbons; as well as oxygen, an essential reactant. An infrared furnace is used to rapidly (few seconds) heat (up to 800 °C) a small sample of combustible material, while output gases are monitored, with 1 s resolution, using a multi-component gas analyzer. Systematic measurements of PMMA, a thermoplastic, are presented. Ultimately these results will be used to provide first responders with remote knowledge of the type of fire prior to entering a site.

I. INTRODUCTION

Current advances in sensor technology and wireless communication systems offer the opportunity to detect uncontrolled fires inside enclosed spaces in the their nascent state prior to major damage to property or loss of human life. By comparing the “burn signatures” of various materials, one could develop a reference table for first responders to remotely identify the type of fire. For example a smoldering fire, noted by its exceptionally low oxygen concentration, has the potential to burst into flames upon influx of oxygen if, for example, one opens a door.

Although there have been many efforts to quantify the products of combustion and pyrolysis, most studies have been directed primarily at determining the products themselves, with a secondary focus on determining whether or not their concentrations, over the course of an experiment, exceed a threshold value [1].

II. SETUP

A schematic of our time-resolved materials characterization system is shown in Figure 1. The sample is placed inside a hollow cylindrical graphite crucible, for uniform heating, inside a quartz furnace tube. The quartz is used so that the experiment is kept in a closed and controlled environment, while still transmitting infrared radiation to the sample. The specimen is radially heated externally by the graphite crucible as well as internally by a graphite skewer. Graphite was specifically chosen for this experiment because it is an excellent thermal conductor, with a thermal conductivity of 240 W/m°C [2]. Since the graphite is black, it efficiently absorbs infrared radiation, which consequently converts into heat energy, and ensures sufficient heating of the sample. Additionally, graphite is chemically inert, even at very high temperatures.

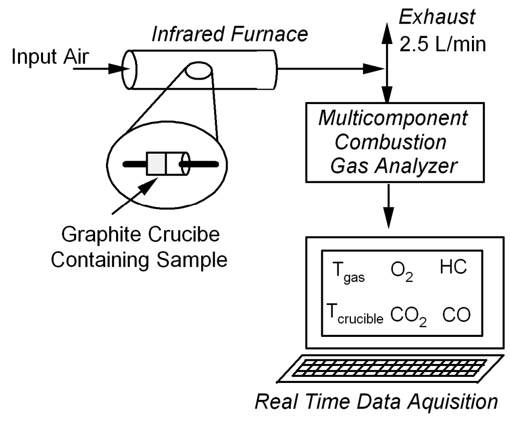

Figure 1. Schematic of time-resolved materials characterization system

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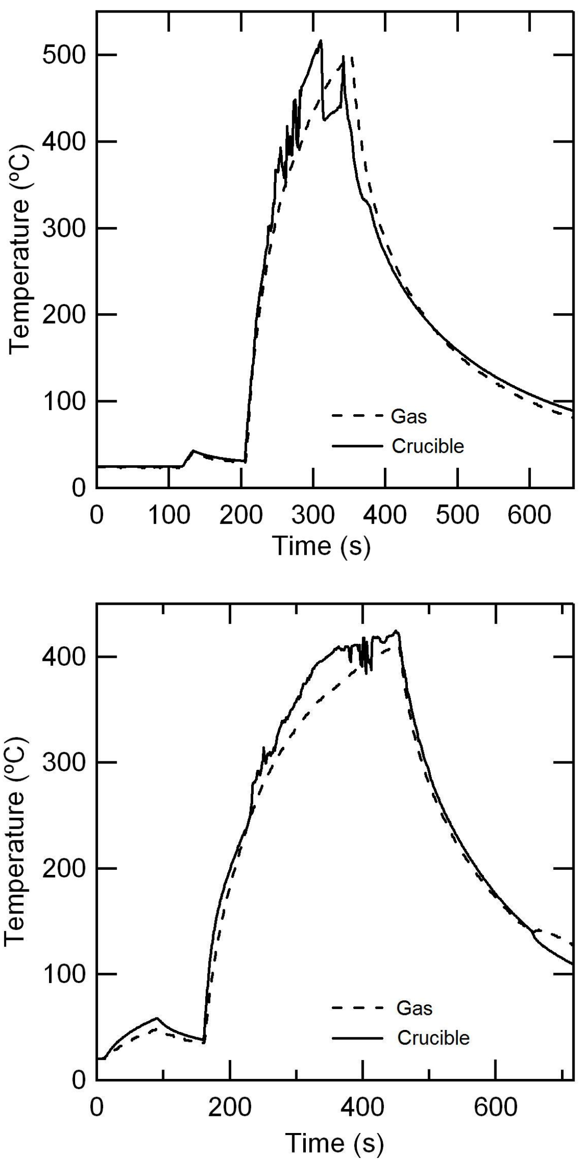

Figure 2. Crucible (solid line) and gas (dashed line) temperature profiles for two separate (500 °C and 450 °C) heating profiles.

An array of infrared lamps allows the material to be quickly heated up to 1100 °C in a repeatable and controlled manner. The furnace can heat to 90% output within 3 seconds and dissipate 90% of the heat within 5 seconds [3]. The system uses ambient air to fuel its combustion, with the draw rate controlled by a variable exhaust pump. The temperatures of various positions in and around the furnace are monitored by K-type thermocouples with a sampling rate of 2 samples per second. The product gases are sampled by the probe from the combustion gas analyzer, which is placed within 2 mm of the crucible. A real-time LabVIEW based data acquisition system monitors and logs, at 1 sample per second, logs the crucible and gas temperatures, as well as directly measures O_2, CO_2, CO and total hydrocarbons with resolutions of 0.1 % volume, 0.01 % volume, 1 ppm and 0.1% LEL respectively [4]. The gas analyzer used in this experiment was specifically chosen because it has the ability to directly measure CO_2 concentration using an NDIR sensor as opposed to calculating it from O_2 consumption. Fig. 2 demonstrates the degree to which the gas temperature and crucible temperature track each other during two different heating profiles.

III. RESULTS

The first benchmark material being investigated is poly (methyl methacrylate) (PMMA). The specimen undergoes pre-combustion pyrolysis, prior to actual ignition and subsequent flaming. PMMA was chosen because it is an "ideal gasifying solid," meaning it undergoes a clean combustion and leaves no char or residue after the process completes. The PMMA specimens begin as solids, undergo a glass transition, and then begin to pyrolyze from the surface inwards. By varying the heating rate of the sample, these phases become more resolvable.

Studies have been conducted to accurately determine the temperature at which pyrolysis occurs in PMMA. Temperatures of 450 ºC [5] and 500 ºC [6] have been reported by two of these studies. Initial tests were ran in this temperature range. The results from 0.25 g PMMA heated to 500 °C with a 5 L/min draw rate are given in Fig. 3. The product gases CO and HC peak around 445 °C, whereas the reactant O_2 is consumed over a broader temperature range.

It is important to note the consistent relative time order of each of the gas peaks. Hydrocarbon is the first of the product gases to peak, indicating when the initiation of pyrolysis, appearing at 304 seconds. The next gas produced is carbon monoxide, which appears at 310 seconds. Lastly, carbon dioxide peaks while oxygen is depleted almost simultaneously, appearing at 315 and 317 seconds respectively. This last step suggests the imminent approach of combustion.

After examining both the temporal order of gas production as well as the relative magnitude of the gas signals, a 'burn signature' can be made for each specific material. Since the magnitude of the gas products will be proportional to the size of the sample being burned, the burn signature can also be used to deduce the amount of material in a combustion situation. By studying the product and reactant profiles for a variety of time and temperature cycles we will develop a library of the pre-combustion signatures of various common materials found in buildings.

IV. CONCLUSION

After a number of assorted materials have been characterized, a library of burn signatures will be created. Each material will have a burn signature, consisting of an auto-ignition temperature and the expected concentration of each of the combustion gases based on the current temperature. Using a sensor array to measure temperature and gas concentrations, in combination with the library of burn signatures, our goal is to enable first responders to determine what materials in a room are burning before they enter. Technology based on this method could make incipient fire

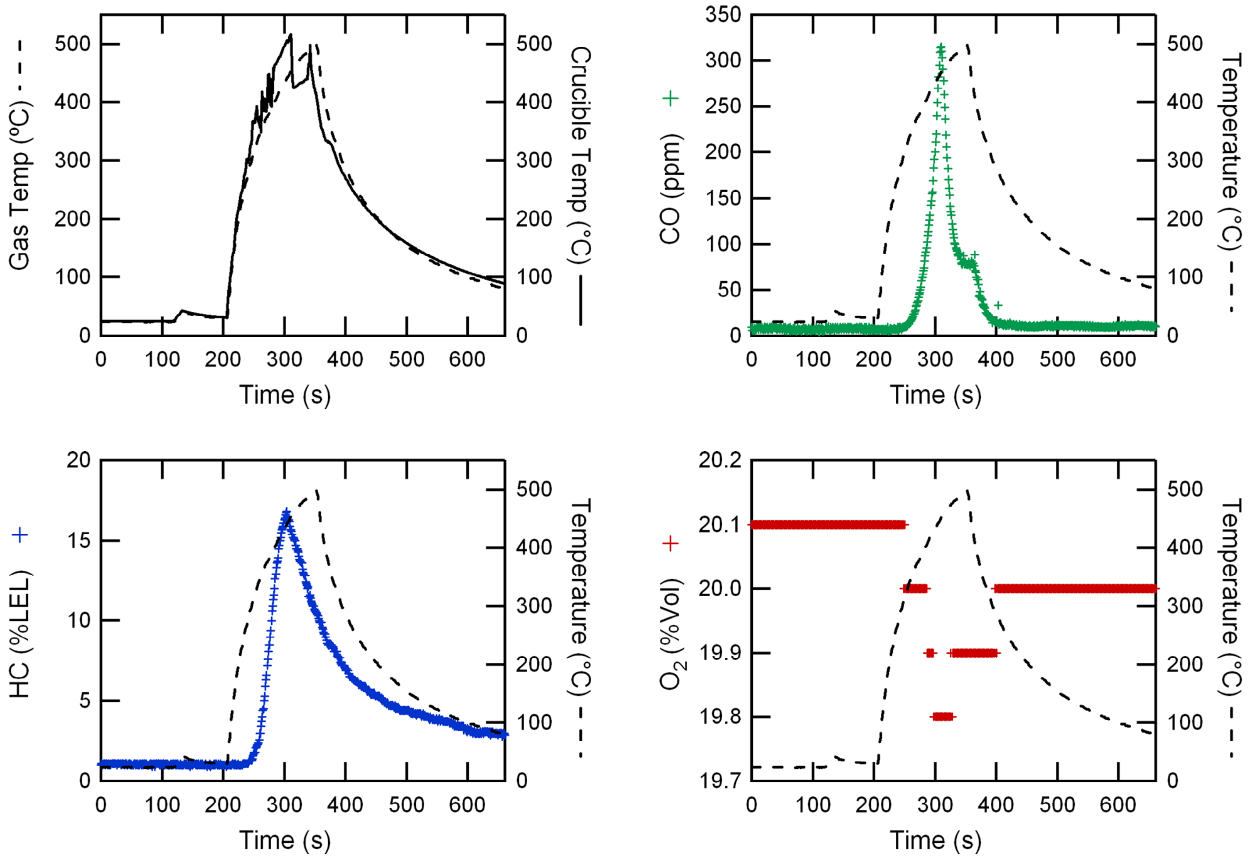

Figure 3. Real-time (1 s data interval) measurements of exhaust gas temperature, crucible temperature, CO, un-burnt hydro-carbons and O_2 for a PMMA (thermo-plastic) sample heated to 500 °C with a 5 L/min draw rate.

detection and diagnostics relatively practical, and therefore potentially decrease fire-related injuries, deaths, and costly property damage.

Future work will address materials other than the "test" material PMMA. One such material is cellulose, for which some measurements have already been made. The difficulty with cellulose, however, is that under slow heating it produces large quantities of tars which foul air filters. Under rapid heating we anticipate that this setback will be alleviated. Later work will also address non-traditional and new synthetic materials. Among these materials are composites such as thermoplastic/wood fiber blends, which have many applications in structures and buildings, and other new composite materials [7]. Composites often have excellent strength properties, but their thermal properties, including resistance to ignition and fire, can negate the gains made in the area of strength.

V. ACKNOWLEDGMENT

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