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A Photoacoustic Technique for Measuring Soot Deposition on Surfaces

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Abstract: This study investigates a soot deposition measurement technique that relies on the photoacoustic effect. A non-invasive and reliable tool to measure soot deposition would be helpful for fire investigators to quantify burn patterns in a fire scene. Soot was deposited on drywall and metal substrates mounted 97 cm to 158 cm above a 13 kW propene diffusion flame burner, and the mass deposited was measured gravimetrically. The soot coated substrates were perturbed with a camera flash of up to 600 J in 0.0045 s, and the photoacoustic response of the soot was measured by a microphone in the form of the peak sound pressure. The results showed a log-based correlation between the acoustic response and the measured soot mass load, a correlation that was dependent on the flash intensity. Notably, the photoacoustic response of soot deposited on both drywall and metal substrates was the same within the experimental uncertainties.
Keywords: photoacoustic, soot deposition

1. Introduction

In forensic fire reconstruction, investigators attempt to draw conclusions about fire origin, the direction of fire progression, and the duration of fire exposure by relying on the subjective interpretation of post-fire burn patterns. This analysis involves characterizing the soot that makes up burn patterns on surfaces, and linking the soot deposition to critical elements of the fire. In fire research, soot deposition measurements are also important for validating life-safety predictions, such as visibility and smoke toxicity. This is because the deposition represents a sink in the mass balance of carbon and thus affects aerosol smoke concentration. Soot deposition mechanisms are understood to be thermal gradients near surfaces (thermophoresis), turbulence, and gravity. However, the ability to accurately predict soot deposition in fires has been limited by the measurement difficulties of the fire conditions and the soot deposition itself.

Because soot is an effective broadband light absorber, it generates an acoustic response when exposed to a pulsed light source. Soot is effective at absorbing the photons, which causes rapid heating, but the heat is quickly dissipated. The rapid heating and cooling results in rapid expansion and contraction of the soot, which results in an audible noise. This photoacoustic response of soot has been used to measure the aerosol concentration of soot and soot emissions [1–4].

Previous methods to characterize soot deposition have demonstrated various limitations. A non-invasive technique relying on grayscale image analysis [5] requires consistent lighting, uniform grayscale coloring, and opacity of the substrate. Also, this method cannot measure additional deposition when surfaces are already coated, limiting the method's applicability in the field. Methods that provide point measurements of deposition, such as direct gravimetric analysis and conductometric gauges [6, 7], can provide high accuracy (gravimetric) or time-resolution (conductance), but these methods require modification of the substrate prior to exposure. Therefore, this study evaluates a reliable non-invasive measurement technique for soot deposition that leverages soot's photoacoustic properties and is independent of the substrate surface.

2. Methods/Experimental

The feasibility of photoacoustic measurements to determine the amount of soot deposition was evaluated using substrates typically found in buildings, such as drywall and metal (stainless steel) surfaces. Soot was deposited on the substrates using a 13 kW propene fire in a 10 cm diameter sand burner for a 30 min exposure time. The 30 cm $\times$ 46 cm substrates were mounted directly above the burner at different heights from the burner surface to deposit different amounts of soot. The drywall substrates were 1.27 cm thick and mounted at 97 cm, 128 cm, and 158 cm above the burner surface. The stainless steel substrates were 0.79 cm thick and collected deposition at 97 cm and 158 cm from the burner surface. In all cases, the substrate was mounted well above the visible flame of the fire.

After deposition, the soot coated substrate was placed in front of the photoacoustic measurement setup shown in Figure 1 to measure the soot's photoacoustic response. The substrate was mounted vertically on an aluminum frame. The light source was a commercial camera flash pointed at the center of the substrate, approximately 7.0 cm away. Two flash settings were used to produce different light intensities, 600 J in 0.0045 s and 2.3 J in 0.0001 s. The acoustic measurement device was a microphone with high sensitivity, positioned between the flash and the substrate, approximately 0.5 cm from the substrate. The microphone signal was recorded and processed to provide the acoustic response to the flash in the form of sound pressure over time.

The amount of soot deposition at each condition was confirmed using gravimetric targets, similar to those used in Mensch and Cleary [8]. A second substrate was prepared for each condition with five pre-weighed aluminum foil targets, 0.03 mm thick, on the substrate. The targets were taped to the substrate to expose a square area of 2.52 cm^2 to the soot deposition. After the soot was deposited, the tape was removed with tweezers, and the change in mass of the target over the target area provided the soot load. One target was taped in the center of the substrate, and the other four were on each side of the center target at a distance of 5 cm from the center target. The five soot load measurements on each substrate were averaged together to compare to the photoacoustic response for that substrate condition.

3. Results and Discussion

The soot deposition mass load measurements are plotted in Figure 2 for all gravimetric targets as a function of height above the burner for the different substrate types. Soot deposition decreases as the burner is moved away from the substrate for the 30 min exposure. There is more scatter in the target measurements when the substrate is closest to the burner, at 97 cm, compared to the targets at the other two heights. This is likely due to spatial variation in the deposition at 97 cm, while the plume has more opportunity to mix and spread when the substrate is farther away. Comparing

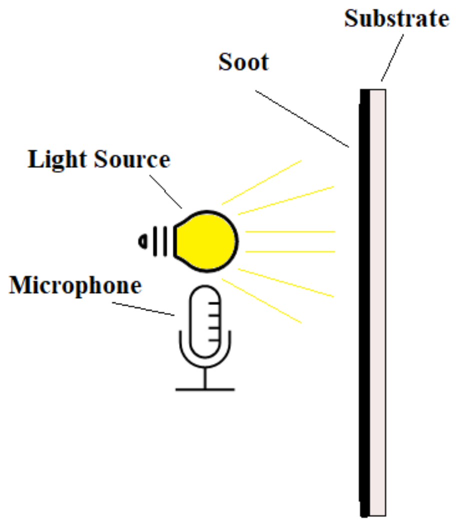


Figure 1: Diagram of photoacoustic measurement setup.

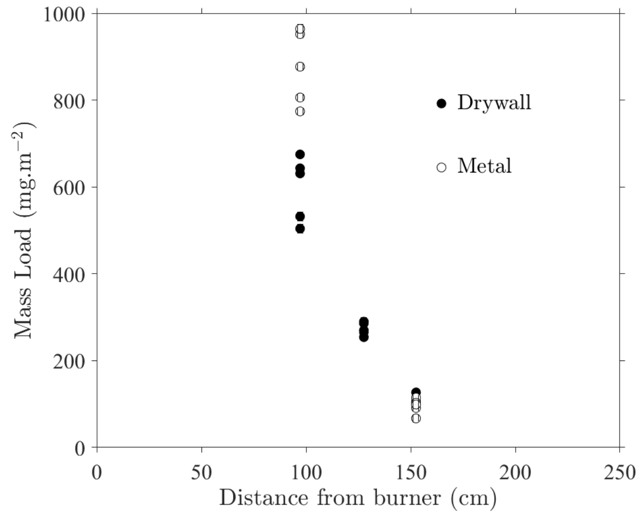
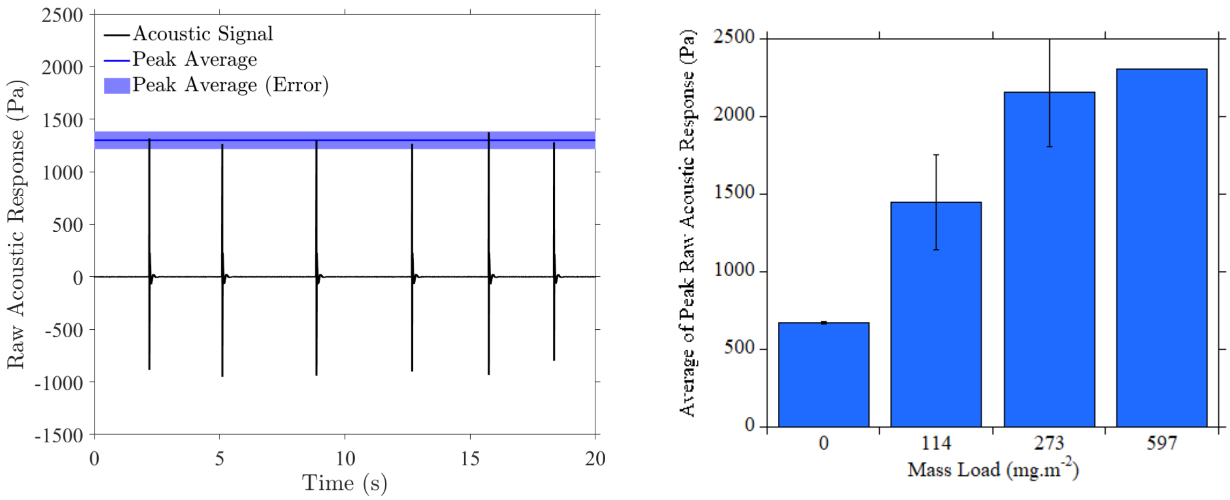


Figure 2: Mass load of soot after a 30 min exposure as a function of substrate height above the burner.

the drywall to metal substrates, there is more soot deposition measured on the metal at the 97 cm height, but little difference between the substrates at the 158 cm height.

Repeated measurements of the raw acoustic response of soot deposition are shown in Figure 3a for a drywall board with 114 mg/m^2 mass load. These measurements are taken for flashes a few seconds apart at the 600 J light setting, and the average peak and associated standard uncertainty (95 % confidence) are shown in blue. Note that each response has both a positive and negative peak in the sound pressure. Figure 3a demonstrates the repeatability of the sound pressure measurement because there is no trend in the raw acoustic response with repeated exposures. Three positive peak values are averaged together to determine the raw photoacoustic response for each experimental case. Figure 3b shows the averages of the peak values of the raw acoustic response for four different mass load cases on drywall at the 600 J flash setting. Error bars show the 95 % uncertainty from the three repeated measurements. The average values increase with the soot mass load. For the blank substrate without any soot, there is still a measured sound pressure peak, which is likely a result of the sound coming from the flash firing. Therefore, the average peak of the blank substrate is subtracted from the average peak of the soot's acoustic response for correlation with the soot mass load.

The photoacoustic response of each substrate is plotted in Figure 4 as a function of the average soot mass load measured for that experimental condition. Drywall results are presented as circles, and metal results are presented as triangles. Filled symbols show the responses from the higher intensity flash, 600 J, and open symbols show the responses from the lower intensity flash, 2.3 J. Repeated cases for the drywall substrate with the high-intensity flash are shown in blue, showing good agreement with each other. The error bars show the 95 % expanded uncertainty of the average acoustic response and the average mass load measurements for each substrate. Because the photoacoustic response flattens as the mass load increases, log-based fits were used to correlate the acoustic response to the mass load. As the mass load increases, the thickness of the soot layer grows, and it becomes more difficult to expose all of the soot to the flash, limiting the photoacous-



(a) (b)

Figure 3: Measurements of the raw acoustic response of soot deposited on drywall with the 600 J light setting, showing (a) repeated measurements on a board with 114 mg/m^2 along with the average peak value and associated error (95 % confidence) and (b) the averages of raw positive peak values for different mass loads along with 95 % uncertainty.

tic response that could be measured if the mass load increases further. There may also be a limit of detection for mass loads less than 100 mg/m^2, which has not yet been determined. Two different log-based curve fits are plotted for the two flash intensities, which intersect the error bars of most of the data points. The two curve fits show that, as expected, the acoustic response is lower for a lower flash intensity. Figure 4 also demonstrates that the photoacoustic response is similar for both drywall and metal substrates. Using the correlations in Figure 4, measurements of the photoacoustic response with the same flash and microphone setup can be used to quantify the soot mass load.

4. Conclusions

This study investigated a non-invasive technique to determine soot deposition on surfaces. The technique measured the photoacoustic response of the soot to a flash of light, which was plotted against gravimetric measurements to give a log-based correlation based solely on the flash intensity. The results demonstrated the repeatability of the results and independence of the response to different substrates. The study demonstrated the potential of photoacoustic measurements to provide a better understanding of soot deposition, both for applications in fire research and for analysis of burn patterns in fire investigations.

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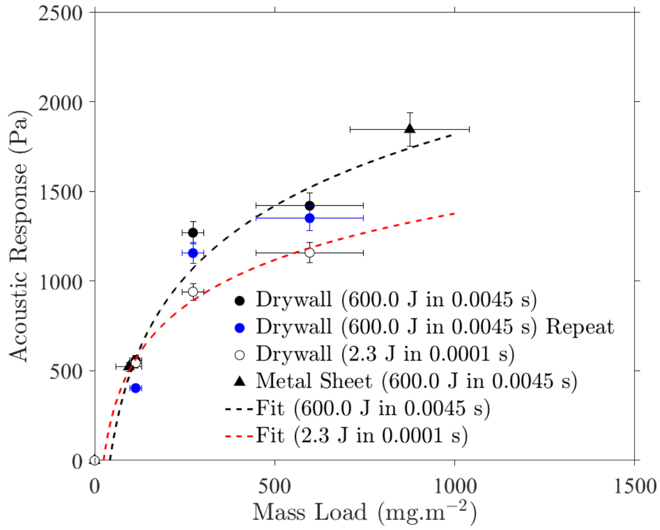

Figure 4: Correlation of the average acoustic response to the average mass loading for each substrate case. Different curve fits are drawn for the two different flash settings. Error bars show the 95 % expanded uncertainty of the average measurement for each substrate.

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