

Respirable Particles and Gas Contaminants Emissions from a Desktop Laser Cutter and Engraver

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ABSTRACT

Airborne contaminants produced during the laser cutting processes are hazardous substances produced as byproducts during laser cutting or engraving operations. These contaminants include respirable particulates, volatile organic compounds (VOCs), and other toxic substances that pose health risks to humans. As desktop laser cutting/engraving technology gains popularity, addressing the potential health hazards associated with airborne contaminants is critical. This study aimed to evaluate the concentrations of respirable particles, sub-half-micron particles, VOCs, and carbon monoxide (CO) that are emitted during laser cutting or engraving processes. The experimental matrix consisted of four materials (cardboard, wood, plastic, and glass) and three currents (10 amp, 15 amp, 20 amp), while also assessing the efficiency of exhaust ventilation. The results showed that the interaction of materials, currents, and ventilation significantly influenced emission concentrations of respirable particulate matter. Cardboard consistently exhibited the highest concentration of respirable particulate matter of $253.9 \pm 47.6 \text{ mg m}^{-3}$ and an average emission rate of sub-half-micron particles of $5.8 \times 10^{10} \text{ \# min}^{-1}$, characterized by the smallest geometric mean diameter of 53 nm in the absence of ventilation. The extremely high emission highlighted the potential of ultrafine particle exposures and health risks from cutting cardboard. Conversely, glass demonstrated excellent resilience to thermal cutting, resulting in lower particle emissions. Wood and plastic materials showed intermediate levels of respirable and ultrafine particle production compared to cardboard and glass. Materials with higher carbon content, such as wood and cardboard, generated higher levels of VOCs and CO, compared to plastic (high VOC but no CO emissions) and glass (no VOC nor CO emission). Additionally, implementing ventilation control during laser cutting or engraving processes is highly recommended, as it effectively reduces the emissions of respirable particles and completely removes gaseous contaminants.

Keywords: Respirable particles, Gas Contaminants, Volatile organic compounds, Desktop laser cutter, Laser engraving

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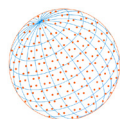
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1 INTRODUCTION

Laser-based cutting technology is rapidly expanding in various industrial and clinical occupational settings (Kiefer and Moss, 1997; Lippert *et al.*, 2014; Walter *et al.*, 2014; Fonseca *et al.*, 2015). During laser cutting processes, many airborne contaminants can be emitted through the abrasion and incineration of materials due to thermal and photolytic interactions (Horseley, 2015). These airborne contaminants comprise complex mixtures of respirable particulates, volatile organic compounds (VOCs), and other harmful gaseous substances that can pose health risks to humans when inhaled (Haferkamp *et al.*, 1997). Laser technology is commonly used in many sectors, e.g., it is estimated that approximately 500,000 healthcare workers, including surgeons, nurses, anesthesiologists, and surgical technologists, are exposed to laser-generated air contaminants (LGACs) each year (OSHA, 2008).



The use of desktop laser cutters/engravers has gained significant popularity and finds applications in a wide range of industries. These machines can cut various materials such as wood, plastic, and leather, utilizing a thermal process to etch the base medium (Haferkamp *et al.*, 1997). The intense and high-temperature nature of the laser-cutting process leads to the generation of substantial amounts of gases and smoke, which enter the workspace in the form of respirable particulate matter (Haferkamp *et al.*, 1997, 1998; Daggett *et al.*, 2020). The particles produced during laser material processing are predominantly particles with an aerodynamic diameter of less than 0.1 μm , also known as ultrafine particles (UFP), which can pose potential health hazards, particularly respiratory issues, to workers (Fonseca *et al.*, 2015; Haferkamp *et al.*, 1998; Daggett *et al.*, 2020). It is worth noting that the size, rather than the concentration, of these respirable and ultrafine particles is what primarily contributes to their toxicity to the lungs (Walter *et al.*, 2014; Fonseca *et al.*, 2015). While the characteristics and particle size distribution of airborne contaminants emitted during laser cutting of plastic and composite materials have been studied to some extent, limited data is available for desktop laser cutters/engravers (Chan *et al.*, 2016; Noskov *et al.*, 2019). Toxic gases, such as volatile organic compounds (VOCs) and carbon monoxide (CO), have been reported to be emitted in high concentrations when using carbon dioxide (CO_2) laser engravers to cut various materials (Kiefer and Moss, 1997; Walter *et al.*, 2014). However, there is a lack of studies investigating the exposure to these gas pollutants when employing a desktop laser cutter/engraver. Therefore, it is necessary to measure their emission concentrations and examine the potential adverse health effects associated with their exposure.

Previous studies have demonstrated that the type of laser application, the processed material, and the implementation of ventilation controls can influence the characteristics of particulate matter and emissions of VOCs (Kiefer and Moss, 1997; Haferkamp *et al.*, 1998; Fonseca *et al.*, 2015). Given the differences in laser power applications and materials being cut, as well as the complexity of laser-generated emission products, it is crucial to assess the exposure to airborne contaminants and gas pollutants generated by desktop laser cutting/engraving machine under different conditions to ensure a safe working environment and mitigate potential hazards to human health. Key aerosol characteristics that need to be evaluated include aerosol mass concentration, particle size distribution, and more. Therefore, this study aimed to assess the emission of respirable particle mass concentration, sub-half-micron particle number concentrations, VOCs, and CO exposure, during the operation of a desktop laser cutting and engraving machine on various materials, using different laser power settings and ventilation controls.

2 METHODS

2.1 Laser Cutter and Engraver Setup

In this study, a desktop 40 W CO_2 laser cutter/engraver (generic brand) was utilized. The laser cutter had the capability to cut or engrave non-metal materials such as wood, stone, leather, crystal, paper, and film, with a maximum cutting depth of 3 mm. It was equipped with a water-cooled laser tube, high-precision stepper motors, and a control board for computer communication. The laser cutting and engraving experiments were conducted in the "chamber", which refers to the enclosed working area within the desktop laser engraving machine. The enclosure ($0.8 \times 0.5 \times 0.25 \text{ m}$) formed a 0.1 m^3 confined space when the lid is closed. Although temperature and relative humidity inside the chamber might affect the formation and growth of particles, we did not monitor these environmental parameters due to the complexity of measuring and variances at different laser currents. Depending on the experimental setup, the chamber can either be ventilated to the building exhaust stack or non-ventilated. The ventilation flow rate of the chamber is 28.3 liters per minute (Lpm) or 260 cubic feet per minute (CFM). Four different materials, namely cardboard, wood, plastic, and glass, were selected for laser cutting. The laser powers were adjustable based on electrical currents, to low (10 A), medium (15 A), and high (20 A). Each combination of parameters (materials, currents, and ventilations) was triplicated.

2.2 Sample Procedure

At the beginning of each experiment, a bucket filled with iced water was used to cool down

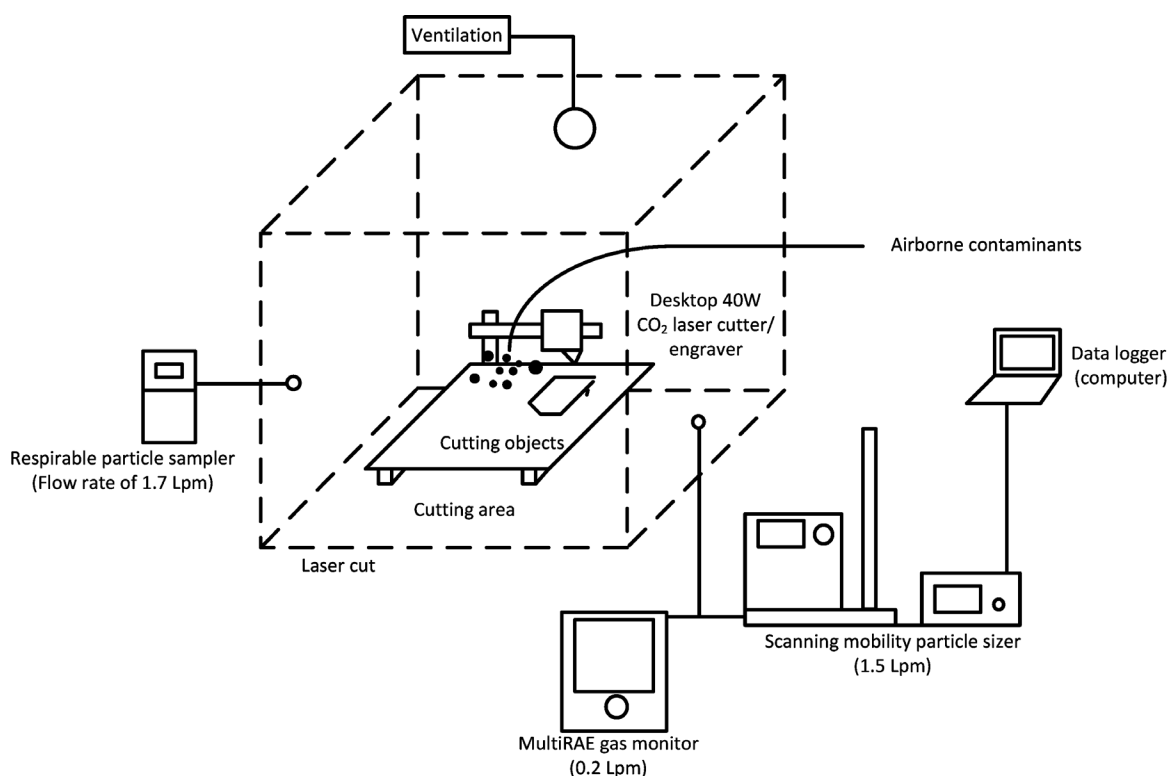
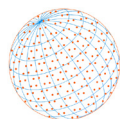
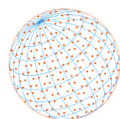


Fig. 1. A schematic diagram of the experimental setup used to measure emitted particles and gas contaminants from a desktop 40-watt CO₂ laser cutter/engraver.

the laser tube. A submersible pump was employed to circulate the water and ensure proper cooling. The water flow was verified after powering on the system. The laser cutter also incorporated a water-break safety feature, which automatically cut off power if the laser tube experienced low water levels. For each experimental session, the laser switch was engaged and tested prior to the experiment. The cutting process was controlled using MoshiDraw (MoshiSoft, Chifeng, China), which generated a circular shape with a laser-engaged period of 5 minutes. The laser currents were adjusted using a knob on the laser cutter. The chamber ventilation was achieved by connecting a flexible pipe to an adjacent lab fume hood stack. The chamber was evacuated for a minimum of 5 minutes between each experimental session using the built-in ventilation. A shop-vac was also employed to remove any residual ash or dust from the testing chamber. A schematic figure of the experimental setup is shown in Fig. 1.

2.2.1 Collection of respirable particles

Respirable particles were collected using a Dorr-Oliver cyclone personal breathing zone respirable dust sampler (SKC Inc., Eighty Four, PA) and an SKC air sampling pump (224-PCXR4, SKC Inc.). The pumps were calibrated to a flow rate of 1.7 Lpm using a DryCal® DC-Lite frictionless piston calibrator (Mesa Labs, Lakewood, CO). The samples were collected on 5- μ m pore size polyvinyl chloride (PVC) filters placed in 37-mm 2-piece cassettes (SKC Inc., Eighty Four, PA), with a mass determination limits of less than 3 μ g (Kuo *et al.*, 2015). The PVC filters were then transferred to a controlled environmental chamber with a relative humidity of 50 percent and left inside for at least 12 hours. The microgram scale (Cahn Model C-33, Orion Research, Beverly, MA) was calibrated using a 200-mg weight and verified to be static-free. The PVC filters were weighed three times, and the pre-weights were recorded. The filters were then placed back into their respective pre-banded SKC cassettes. After sampling and 12 hours in the controlled environmental chamber, the post-weights of the PVC filters were obtained and recorded. The average dust exposure was calculated by dividing the difference in filter weights by the sampled air volume. Blanks were obtained randomly between sessions to determine the background level.



2.2.2 Sub-half-micron particle size distribution

Respirable particles are characterized by an aerodynamic diameter of 10 micrometers (μm) or less, whereas sub-half-micro particles are defined as particles with sizes less than 0.5 μm . The collection of sub-half-micron particles allows for a more detailed analysis of smaller particles that may not be captured by the PVC filters used for respirable particles. The particle size distribution of sub-half-micron aerosols was measured using a scanning mobility particle sizer (SMPS) machine consisting of an electrostatic classifier (TSI 3080, Minneapolis, MN) and a condensation particle counter (TSI 3775, Minneapolis, MN). The condensation particle counter was warmed up for 20 minutes or until the status bar light turned green before each sampling. The flow rate of the SMPS sampling inlet was set at 1.5 Lpm, with a sheath air flow of 3 Lpm. This combination allowed for a measurable range of 16.8 to 532 nm (electric mobility size). A rubber conductive tubing was placed in the chamber to draw the aerosol-loaded airstream to the sampling inlet. For each experimental condition, the SMPS took one environmental sample, followed by ten actual samples of 60 seconds each.

2.3 Measurement of TVOC and CO

Total volatile organic compounds (TVOC) and carbon monoxide (CO) were monitored using a multi-gas detector (Honeywell Pro-Rae, Lincolnshire, IL) calibrated to 100 ppm VOC using isobutylene. The detection limit of the MultiRAE instrument is 0.1 ppm (Pavelchak *et al.*, 2009). The extended sampling port of the detector was inserted into the chamber, and an environmental sample was taken for five minutes before each session. The data from the Pro-Rae multi-gas detector was extracted and synchronized with the experimental event timeline using the Pro-Rae Suite software.

2.4 Calculations of Emission Rates

The mass of respirable particulate matter collected on the filters was calculated using the following equation based on the pre- and post-weights of the filters, as shown in Eq. (1):

$$\text{mass (mg)} = \text{postweight} - \text{preweight} \quad (1)$$

The mass concentration of respirable particles (mg m^{-3}) was calculated based on Eq. (2) using the collected mass, the sampling period (5 minutes), and the sampling air flow rate (1.7 Lpm).

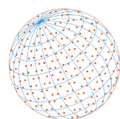
$$C_{\text{mass}} = \frac{\text{mass (mg)}}{1.7 \text{ Lpm} \times 5 \text{ min} \times \frac{1 \text{ m}^3}{1000 \text{ L}}} \quad (2)$$

The particle emission rate ($\# \text{ min}^{-1}$) of particles smaller than 532 nm was calculated based on a single loss factor (KL), considering surface loss and intra-/inter-coagulation loss, without accounting for ventilation loss. KL was calculated using linear regression from the natural logarithmic plot of the time-series data during the post-cutting/engraving period (5–10 minutes) when emission stopped and loss dominated, as shown in Eq. (3).

$$K_L = \frac{\ln(C_{10}/C_5)}{5} \quad (3)$$

where C_5 and C_{10} are the number concentrations at 5 minutes and 10 minutes, respectively ($\# \text{ cm}^{-3}$). The particle count emission rate ($E_{P-\Delta t}$) at a given time t (min) was then calculated using the Eq. (4) (Bhangar *et al.*, 2011; Floyd *et al.*, 2017).

$$E_{P-\Delta t} = V \times \left(\frac{C_{t+1} - C_t}{\Delta t} + K_L \times C_t \right) \quad (4)$$



where C_{t+1} and C_t are the discrete number concentrations at time t and $t + 1$, Δt is the sampling interval of 1 minute, and V is the volume of the chamber (16.8 L). The average emission rate (E_p) was calculated by summing the time-varying particle count emission rates ($E_{p-\Delta t}$) and dividing by the total time (t), as shown in Eq. (5).

$$E_p = \frac{\sum E_{p-\Delta t} \Delta t}{t} \quad (5)$$

The average concentrations of VOC and CO were calculated by averaging their respective sampling periods with a 1-second interval.

2.5 Statistical Analysis

Data analysis was performed using IBM SPSS Statistics version 23 (IBM Inc., Armonk, NY). Analysis of variance (ANOVA) was conducted to assess the mass concentration of respirable particles considering the following parameters: material types, currents, and ventilation conditions, given that the data met the assumptions of normality and equal variance. For particle emission rates, which did not consider ventilation, the parameters were reduced to two (material types and currents). Two-way ANOVA was employed to analyze the statistical differences. The same approach was applied to evaluate the impact of material types and currents on TVOC and CO concentrations, as ventilation was not considered in the gaseous measurements.

3 RESULTS AND DISCUSSION

3.1 Respirable Particulate Mass Concentration

The mass concentrations of respirable particles were calculated by dividing the gravimetric measurement results by the sampled air volume (flow rate of the sampling pump multiplied by the sampling minutes, $1.7 \text{ Lpm} \times 5 \text{ min}$). A three-way ANOVA was conducted to analyze the average respirable particulate mass concentrations, and statistical significance was found within each parameter (materials, currents, and ventilation) ($p < 0.001$). The interaction among the three factors was also found to be significant in affecting the particle mass concentration ($p < 0.001$), indicating that the effect of one factor is not consistent across all combinations of the other two factors. A strong statistically significant interaction was observed between materials and currents ($p < 0.001$), while no significance ($p > 0.05$) was found in the interaction of materials and ventilation or the interaction of currents and ventilation. Therefore, an unambiguous interpretation of the statistical analysis does not allow for a general principal effect to be concluded.

Fig. 2 illustrates the differences in collected respirable particulate mass concentrations for cutting and engraving four materials under three laser currents and two ventilation conditions. Cardboard and plastic, categorized as cutting materials, exhibited a tendency to be completely penetrated by the laser, while wood and glass, classified as engraving materials, demonstrated more resistance to thermal energy, resulting in minor surface marks. Ventilation control reduced respirable particle exposure by an average of 61%. In both ventilation conditions, cardboard produced the highest respirable particles of $253.9 \pm 47.6 \text{ mg m}^{-3}$ at high laser powers without ventilation, while glass produced the least particles at low laser powers with ventilation ($7.9 \pm 8.6 \text{ mg m}^{-3}$). Wood emitted the highest respirable particles of $164.3 \pm 55.4 \text{ mg m}^{-3}$ at low currents without exhaust ventilation, but ventilation significantly ($p < 0.05$) reduced the particle concentration more than 77%. When ventilation was turned off, cardboard and plastic showed similar trends in dependency on currents, with respirable particle mass concentrations increasing with increasing currents. High currents produced significantly ($p < 0.05$) higher respirable particle mass concentrations than low and medium currents for materials other than wood. However, when ventilation was turned on, medium current resulted in the highest particle emissions from cutting and engraving cardboard and plastic, while the highest mass concentrations were found in wood and glass at high currents. This finding is consistent with the study conducted by Niu *et al.* (2024), demonstrating that the highest particle emissions during the ventilated laser cutting of leathers were predominantly observed

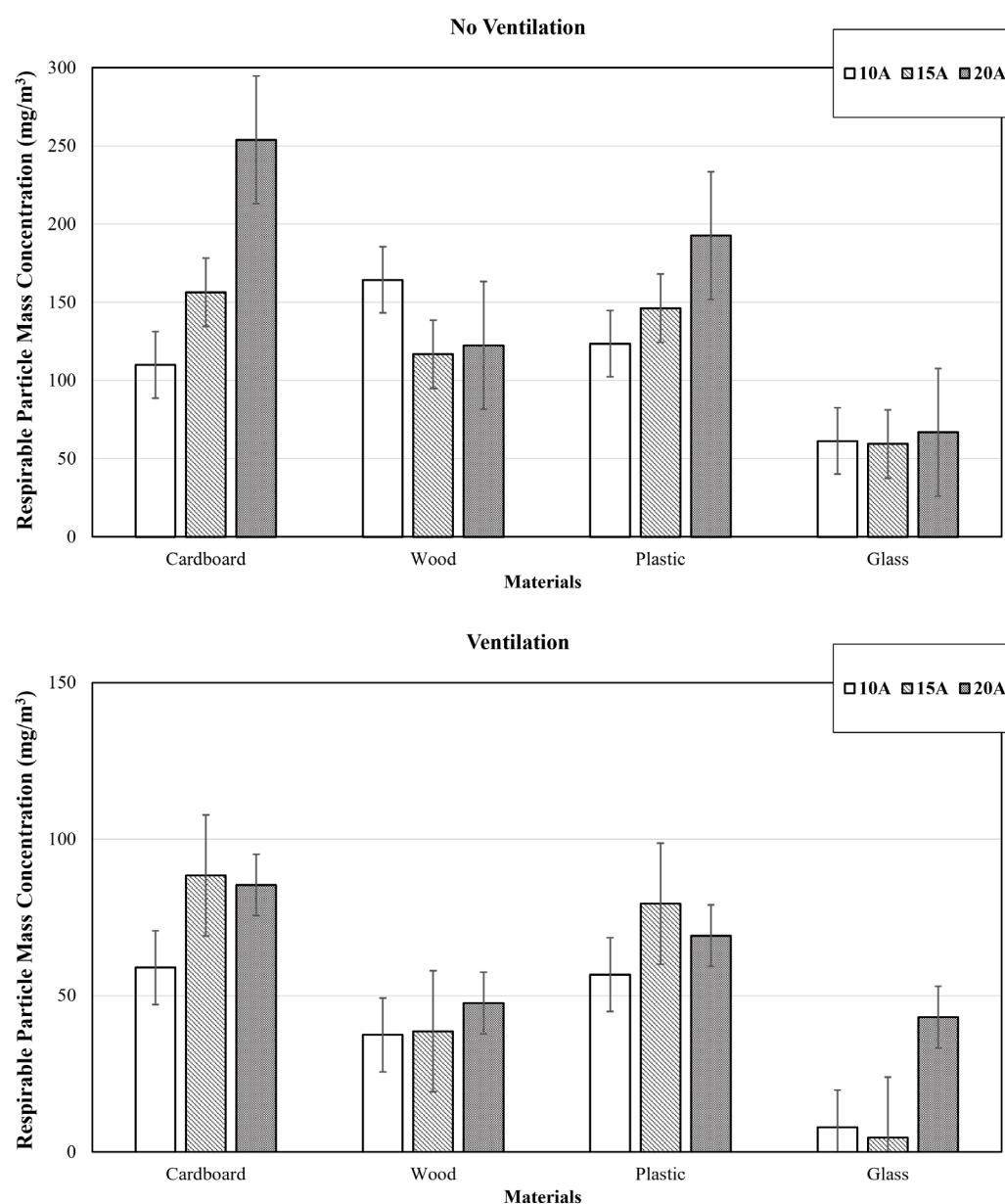
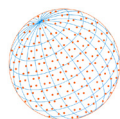
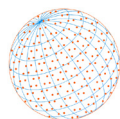


Fig. 2. The mass concentration of respirable particles from a desktop CO₂ laser cutter/engraver measured by gravimetric method for cutting four materials under three laser powers and two ventilation conditions. The error bars represent standard deviation of mass concentrations.

at medium laser power levels. The medium laser power produced a partial penetration of the cutting material, leading to increased particle emissions compared to low power (no penetration) and high power (clean penetration) settings (Niu *et al.*, 2024).

The respirable particulate mass concentrations observed across the four materials studied significantly exceeded both the OSHA permissible exposure limit (PEL) for respirable fraction of particles in general industry (5 mg m⁻³) and the American Conference of Governmental Industrial Hygienists (ACGIH) guideline (3 mg m⁻³) (OSHA, 1998; CDC, 2018). Furthermore, the concentrations also surpassed levels previously documented in various occupational scenarios, such as the respirable particle emission concentrations in operating room settings, and exposure to ultrafine and nanoparticles from laser-processed ceramics (Fonseca *et al.*, 2015; Lopez *et al.*, 2015). The discrepancy can be attributed to two primary factors. Firstly, the respirable particle mass collected in this study came from a 5-minute of laser cutting/engraving process, not a full-work-shift personal



sampling. This shortened duration might lead to an overestimation of exposure due to the intensified particle generation rate within short time frames. Secondly, the particles originated from a desktop laser cutter/engraver located within an enclosed workspace, limiting their dispersion into other areas of the workplace, and confining their presence to the immediate vicinity of the cutting/engraving operation.

Moreover, our data indicates the efficacy of ventilation control in mitigating respirable particle emissions from sampling devices. This finding aligns with the previous studies related to laser-generated particulate matter exposure (Haferkamp *et al.*, 1997; Chan *et al.*, 2016; Daggett *et al.*, 2020, Niu *et al.*, 2024). It is notable how ventilation significantly reduced the respirable particulate mass concentrations across different materials and cutting conditions. This finding emphasizes the necessity of proper ventilation design and maintenance in workplaces, as well as the utilization of portable ventilation units where laser cutting and engraving processes occur.

3.2 Sub-half-micron Particle Emission Rates and Particle Size Distribution

Particle emission rates for particles smaller than 532 nm were calculated based on the time-series data of particle number concentrations without considering ventilation. The ventilation rate of 260 CFM overwhelmed other particle loss mechanisms and could not be used in the calculation of particle emission rates. Two-way ANOVA performed on particle emission rates indicated a statistically significant difference ($p < 0.001$) in the discrepancy among material types. Pairwise multiple comparison tests (Tukey) showed that the particle emission rate of cardboard was significantly higher ($p < 0.05$) than that of wood, plastic, and glass. There was no pairwise statistical difference between wood, plastic, and glass, although their mean particle emission rates differed. Unlike material types, the statistical difference between different currents was not significant enough ($p > 0.05$) to exclude the possibility of sampling variability and randomness. There was also no interaction between currents and material types ($p > 0.05$).

Fig. 3 presents the average particle emission rate in a lognormal scale. Cardboard exhibited the highest particle emission rate across the three currents, averaging $5.8 \times 10^{10} \text{ \# min}^{-1}$, while glass had the lowest emission rate of $6.0 \times 10^7 \text{ \# min}^{-1}$. The particle emission rates for cutting/engraving cardboard and plastic increased with increasing currents, but the opposite trend was observed for cutting wood, where the particle emission rate decreased with increasing current. Glass generated the highest particle emission rate at the medium current. The results of particle emission rates were generally in line with the gravimetric measurements of respirable particulate matter.

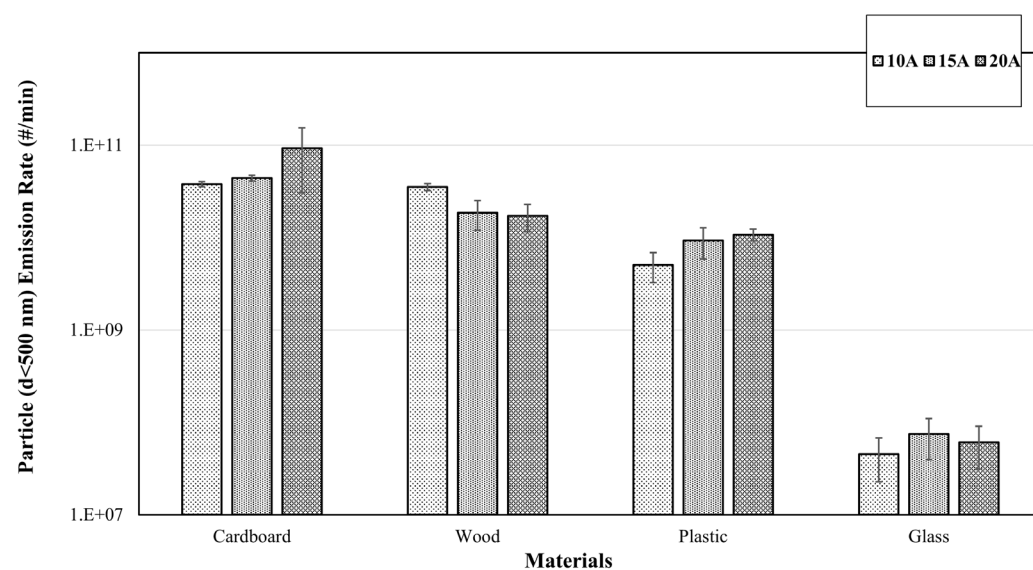
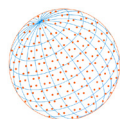


Fig. 3. Particle emission rates (\# min^{-1}) from a desktop CO_2 laser cutter/engraver measured by SMPS for cutting four materials under three laser powers with no ventilation. The error bars represent standard deviation of particle emission rates.



The particle size distribution of particles smaller than 532 nm was recorded for ten minutes at the beginning of each experiment, with a time resolution of 1 minute. The maximum concentration for each experiment usually occurred within the first five minutes during cutting and engraving, followed by decay as particle loss dominated. Since there was no statistical difference among currents, the data was aggregated into material types and ventilation conditions. Fig. 4 displays each material's average maximum particle number concentration and geometric mean diameter (GMD). The GMD ranged from 53 to 162 nm, with cardboard producing the smallest particle sizes and implying higher health risks due to ultrafine particle exposures. Ventilation control was able to reduce particle concentrations to varying degrees. Glass exhibited significantly lower particle concentrations in both ventilation conditions compared to the other three materials. A study conducted by [Ko *et al.* \(2021\)](#) found that the diameter of particles emitted from wood was 151.8 ± 10.9 nm when subjected to an air flow rate of 10 L min^{-1} , which is consistent with our testing data, i.e., 161.6 ± 27.9 nm. However, a substantial distinction arose with respect to particle concentration generated by the wood. [Ko *et al.* \(2021\)](#) reported a markedly lower particle concentration of $(0.4 \pm 0.02) \times 10^5 \text{ particles cm}^{-3}$ compared to our recorded data, which exceeded $1 \times 10^5 \text{ particles cm}^{-3}$. However, the particle concentration emitted from wood was $(0.4 \pm 0.02) \times 10^5 \text{ particles cm}^{-3}$, whereas our data exceeded $1 \times 10^5 \text{ particles cm}^{-3}$. This disparity in particle concentrations between our investigations can be attributed to a temporal variation in the laser cutting duration. Our methodology focused on capturing the maximum particle concentration achieved within the initial five minutes of laser cutting/engraving, while [Ko *et al.* \(2021\)](#) extended their wood processing duration to a full hour. The variation in operational timeline impacts particle emission dynamics, as prolonged processing may lead to a greater accumulation of emitted particles.

Fig. 5 presents the particle size distribution of different materials, showing that most materials had GMDs around the ultrafine range (100 nm) with a one-modal distribution (geometric standard deviation of 1.7–1.9), except for glass, which had a lower-level concentration and distribution (geometric standard deviation > 2.2). The relative contribution of particles below 20 nm and above 200 nm to the total number concentration is minimal for most materials with the exception of glass. The particle size distribution curves of glass display a peak within a range of 100–200 nm with and without ventilation. Similarly, the particle size distribution of cardboard resembled this distribution, with its peak approximately between 40 and 150 nm in both ventilation conditions. In contrast, wood and plastic contribute different particle size distributions with and without ventilation. With ventilation, the particle size range of the peak concentration from wood was

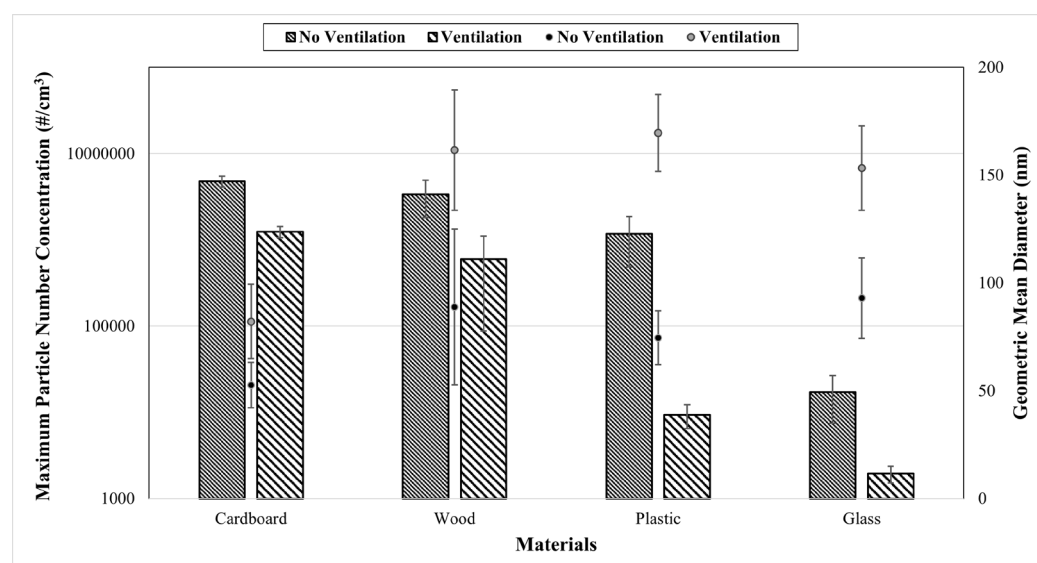


Fig. 4. Maximum particle number concentration ($\# \text{ cm}^{-3}$) on a lognormal scale (left Y axis) and geometric mean diameter (nm) on a linear scale (right Y axis) when laser cutting different materials under two ventilation conditions. The error bars represent standard error of maximum particle number concentrations.

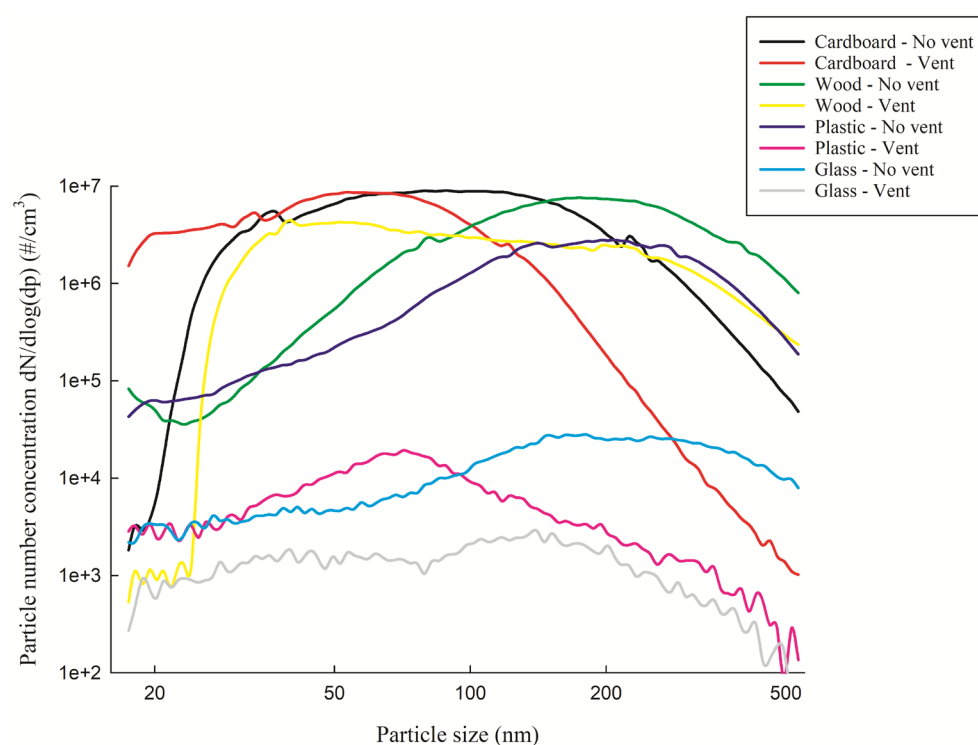
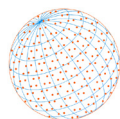


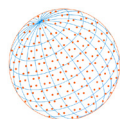
Fig. 5. Particle size distribution when laser cutting different materials under two ventilation conditions.

40–50 nm, whereas plastic was in the range of 60–100 nm. The particles above 150 nm were observed to contribute to the peak number concentration for both materials without ventilation control. Munoz *et al.* (2023) investigated the particle emissions resulting from laser cutting of acrylic plastic and demonstrated a noteworthy correlation between the absence of proper ventilation control and an increase in the production of nanoparticles, a finding that aligns with our findings. However, they reported most particulates to be within a size range from 27.4 to 36.4 nm above 2,821 and 3,075 particles cm^{-3} with ventilation (Munoz *et al.*, 2023). This contrasts our observations, i.e., particles produced from laser-cutting plastic displayed concentrations exceeding 10,000 particles cm^{-3} , with 60–100 nm peak sizes. This variation in particle size and count could be due to differences in the composition of the plastic material subjected to laser cutting and laser powers.

Furthermore, the particle number size distributions suggest a pronounced increase in nanoparticles (< 100 nm) for cardboard and wood when using ventilation, but this trend wasn't evident for other materials. A plausible explanation for this discrepancy could be attributed to the higher carbon content present in cardboard and wood. The carbon-rich composition of these materials facilitates the formation of smaller particles in response to laser cutting or engraving processes, a phenomenon that is accentuated by the introduction of ventilation measures. The synergy between carbon content and laser energy could be fundamental to the elevated nanoparticle emission observed with ventilation for cardboard and wood.

3.3 TVOC and CO Concentrations

Average TVOC concentrations during each experiment were calculated from the time-series data with a resolution of 1 second. When ventilation was turned on, TVOC concentrations were lower than background levels for all experiments, indicating that ventilation effectively removed all VOCs. Glass did not emit any detectable VOCs during the experiment and was excluded from the statistical test. Fig. 6 presents the average TVOC concentrations during the cutting and engraving of different materials. Engraving plastic generated the highest TVOC concentration of 5.7–10.0 ppm compared to cutting cardboard (4.3–6.7 ppm) and wood (3.3–4.4 ppm), while the latter two had no statistically significant difference ($p > 0.05$). High currents resulted in higher TVOC



emissions for cardboard and plastic, while low and medium currents did not show statistically significant variations. There was no statistically significant difference among all three currents ($p > 0.05$) for wood.

Similar to TVOCs, CO concentrations were below the detection limit of the multi-gas detector, that is 0.1 ppm when ventilation was turned on. Both plastic and glass did not produce any detectable CO with or without ventilation. As presented in Fig. 7, the average CO concentrations collected from cutting cardboard and wood were 23.9 ppm and 31.8 ppm, respectively. A two-way ANOVA was performed on cardboard and wood with different currents. While there was a statistical difference between materials ($p < 0.05$), there was no statistical significance among different currents ($p > 0.05$) or interaction between materials and currents ($p > 0.5$). As shown in Fig. 7, wood generated significantly ($p < 0.05$) higher average CO concentrations at different currents than cardboard.

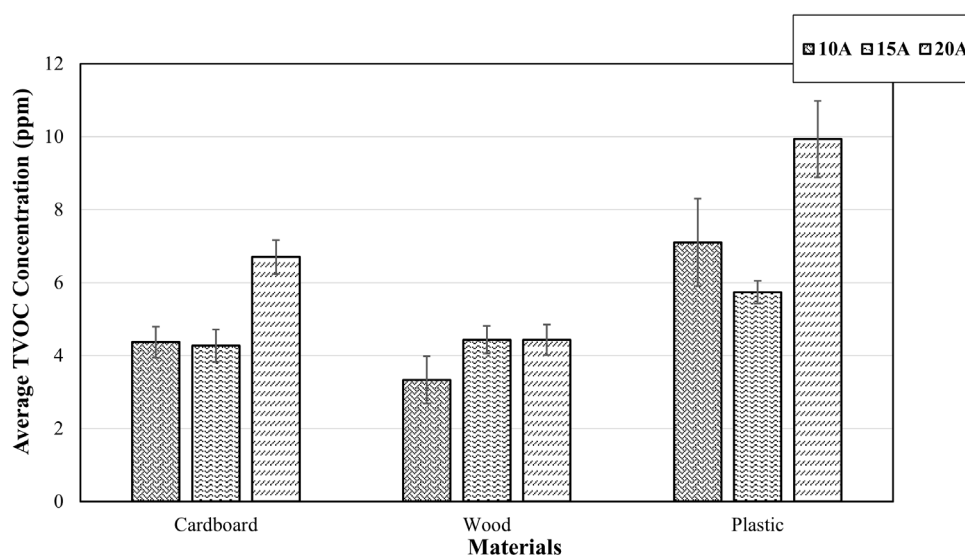


Fig. 6. Average TVOC concentration from a desktop CO₂ laser cutter/engraver measured by Pro-RAE Multi-gas detector for cutting three materials under three laser powers without ventilation. The error bars represent standard deviation of TVOC concentration.

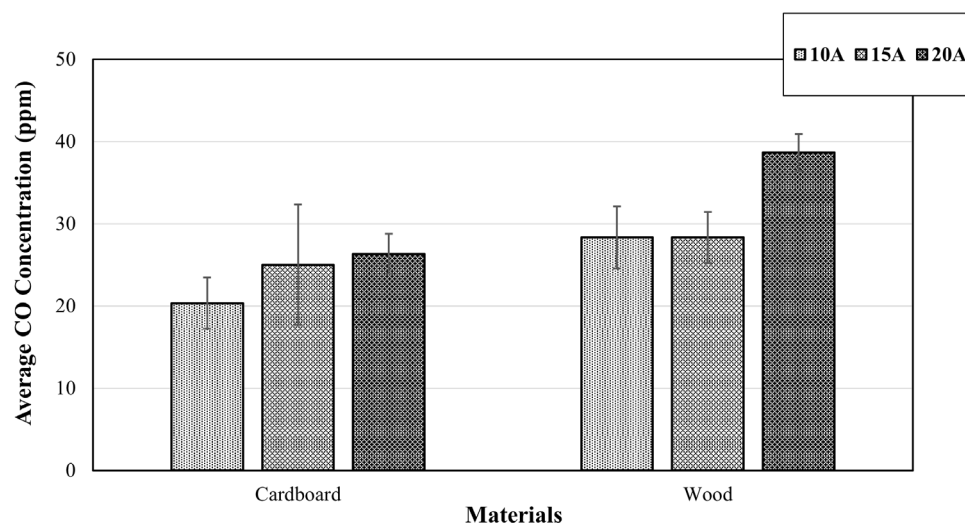
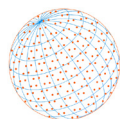


Fig. 7. Average CO concentration from a desktop CO₂ laser cutter/engraver measured by Pro-RAE Multi-gas detector for cutting two materials under three laser powers without ventilation. The error bars represent standard deviation of CO concentration.



Glass did not produce any VOC or CO emission as the main components of glass is silica and boron oxides, which are both resistant to thermal shock and devoid of carbon content. In contrast, plastic emitted significantly higher TVOC levels compared to other materials, but did not produce any CO. Both cardboard and wood emitted TVOC and CO, as expected with their carbon-rich composition. The current had varied impacts on TVOC and CO emissions, respectively. In general, a higher current generally led to more TVOC emission due to thermokinetics, although a statistically significant difference was not observed for wood. CO emissions across different currents were not statistically significant ($p = 0.066$). Wood had a marginally higher CO emission compared to cardboard. All recorded CO concentrations were lower than the OSHA permissible exposure limit of 50 ppm, but higher than the ACGIH threshold limit value (25 ppm) (OSHA, 1998). As with respirable particulate mass and fine particle emission, ventilation proved highly effective, and it is strongly recommended that ventilation is always employed to prevent overexposure to gaseous contaminants.

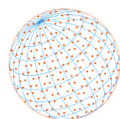
3.4 Limitations of the Study

There are several limitations in this study. We did not explore the composition of VOCs due to the constraints in both timeframe and resources. A follow-up investigation should be performed to comprehensively analyze the specific composition of these VOCs. Additionally, our examination exclusively focuses on sub-half-micron particles, primarily driven by their recognized respiratory implications on human health. A broader range of particles, with particle size distribution ranging from nanometers to 10 microns, should be measured and reported in the follow-up research. In addition, environmental parameters such as temperature and relative humidity were not monitored during the study.

Further, we acknowledged that the experimental procedures were conducted within a controlled laboratory environment, thus deviating from the representative conditions encountered in real occupational settings. Comparison with the occupational limit values is intended to provide a baseline for future studies and contribute to the broader body of knowledge in a specific context. Future research could consider conducting simulations under more realistic conditions, such as studies in larger chambers, fieldwork, or examinations in real-world settings.

4 CONCLUSIONS

This study revealed that laser cutting and engraving operations can generate hazardous air contaminants that pose potential health risks to users. Among all the materials, respirable particulate mass concentrations: Cardboard consistently exhibited the highest concentrations of respirable particulate matter, followed by wood and plastic. Glass showed excellent resilience to thermal cutting, resulting in lower particle emissions. Most materials produced ultrafine particles with a geometric mean diameter in the range of approximately 100 nm. Cardboard had the smallest GMD, indicating the presence of smaller particles. Cardboard had the highest particle emission rates among the materials, while glass had the lowest. Particle emission rates generally increased with higher laser currents. Wood and cardboard, which have higher carbon content, emitted more TVOC and CO compared to plastic and glass. Engraving plastic generated the highest TVOC concentration. Ventilation control was highly effective in reducing the emissions of respirable particles and completely removing gaseous contaminants, including VOCs and CO. Implementing proper ventilation is crucial in creating a safer working environment and minimizing health hazards. Overall, the study emphasizes the importance of considering the materials being processed, laser currents, and ventilation control in laser cutting or engraving operations to mitigate the emission of respirable particles and gas pollutants and ensure the safety of workers. This information is valuable for industries and manufacturers to make informed decisions regarding material selection, process optimization, and equipment adjustments to minimize hazardous emissions during laser operations. Further research and measures should be undertaken to address overexposure to respirable particulate mass and minimize the potential health risks associated with laser-generated air contaminants.

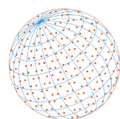


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