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Characterization and Exposure Assessment of Odor Emissions from Laser Cutting of Plastics in the Optical Film Industry

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ABSTRACT

The introduction of lasers as a cutting tool has become an important step in achieving further cost reductions in the multi-functional optical film industry. However, the fumes produced during laser cutting causes an annoying and often unbearable odor in the working environment. To date, little research has been reported in terms of the worker exposure assessment and odorous substances generated in the process of cutting plastics with lasers. This study firstly investigated the worker exposure assessment and the protection efficiency of the carbonyls and phenols when a laser is used to cut polycarbonate (PC) and polyethylene terephthalate (PET), the primary base materials used in optical film industry. Results indicate that the concentrations of these substances increased with the power of the laser. Due to differences in the monomer structures of these materials, a 240 W laser produced a high concentration of phenols (1.56 mg m^{-3}) from PC and a high concentration of carbonyls (20.3 mg m^{-3}) from PET. Without adequate protection and within a one-meter distance, laser cutting PET at the 240 W power level would expose machine operators to 2.74 mg m^{-3} of formaldehyde, which exceeds the regulatory standard of 2.4 mg m^{-3}. An N95 valved active carbon respirator can effectively reduce this concentration to 0.07 mg m^{-3}. However, the result of the masks studies could only reduce concentrations to between 1.88 mg m^{-3} and 2.2 mg m^{-3}, which barely meet the related regulatory standards. In contrast, the installation of local ventilation alone can effectively remove as much as 99% of the gaseous substances produced in the laser cutting of plastics.

Keywords: Laser cutting; Plastic; Carbonyls; Phenols; Protections.

INTRODUCTION

The use of laser cutting for a wide range of materials has been gaining popularity in many industries because of its high precision and efficiency, low deformation and noise, flexibility for many materials, and energy- and material-saving nature (Charschan, 1972). Compared to traditional, mechanical cutting and/or punching methods, laser cutting can greatly reduce the production time and cost needed when working with various materials and complicated preprocesses.

Due to the increasing variety of electronic products that have displaying screens, such as mobile phones, digital cameras, liquid-crystal display (LCD) monitors, and laptops, laser cutting has become an important step in producing multifunctional optical films, one of the critical parts in monitor production. The major type of laser cutting in the optical film industry involves laser sublimation. However, sublimation by laser produces fumes containing toxic air pollutants which pose risks to both the environment and the operators (Sims *et al*., 1993).

A typical optical film has a sandwitch-like structure which is consisted of a protective film, a surface treatment film, an adhesive layer, and a substrate. About 60–70% of optical film is composed of polymers, among them PC and PET, are the most popular (Eguiazabal and Nazabal, 1989).

Both particulates and gases emitted by during laser cutting of some plastics were found and nanoparticles were identified (Kuo *et al*., 2014). The higher levels of nanoparticle exposure were found in unintended emission of nanoparticles (UNP) workplace comparing to large-scale engineered nanoparticle manufacturing workplaces (ENP) and laboratories (Ham *et al*., 2015). However, polymers PC and PET, which are widely used in the optical film industry, do not contain the above-mentioned elements. According to the functional groups of chemicals, there were nine major categories identified for the compounds producing odors, including phenols (mono-, poly-), aldehyde (-CHO) and ketone (>C=O) (Yachigo *et al*., 1988). Many studies have reported that some odor are emitted during the manufacturing processes of plastics (Lewis, 1999; Villberg and Veijanen, 2001; Chou and Wang, 2007). However limited for the odor emissions of carbonyls and phenols have been reported

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(Sims *et al*., 1993). Carbonyls are commonly detected in the indoor or outdoor air in the environment (Bernabe *et al*., 2015; Yao *et al*., 2015; Lü *et al*., 2016). Their concentrations can vary due to seasonal or diurnal effects, and source differences (Guo *al*., 2015; Leuchner *et al*., 2016). Carbonyls are harmful to the human organs, and can have genetic and carcinogenic effects on people who are exposed to them (Sitting, 1974; Bailey *et al*., 1978), while exposure to phenols can affect the hematological and nervous systems, as verified by Risner and Cash (1990). Calabrese and Kenyon (1991) stated that the acute intoxication of phenols might result in a cardiopulmonary arrest or even death.

The aim of the present study is thus to investigate the odors associated with carbonyls and phenols emitted during laser cutting of plastics, including PC and PET, and to assess the exposure of employees to such emissions in an optical film factory at various distances from the source, was well as the effectiveness of the several protection measures.

METHODS

Study Design

This study aimed to investigate odorous substances, carbonyls and phenols, produced when PC and PET films, the primary base materials used in optical films, are cut with laser. The first part involved the sampling and characterization of carbonyls and phenols emitted during laser cutting of PC and PET under different power levels (80 W, 160 W, and 240 W), which are commonly used by major manufactures of functional optical films., Secondly, the workers' exposures to carbonyls and phenols at different distances (0.1 m, 1 m, 3 m, and 7 m) at 240 W were assessed. Thirdly, efficiencies of the respiratory protective equipment (RPE) and the local exhaust ventilation (LEV) against emissions from the laser cutting process were conducted at 240 W.

Laser Cutting and Plastic Substrates

The equipment used in the present study was a CO_2 laser cutter (Preco, Model: SL8600), which has a maximum power of 400 Watts and a wavelength of 10.6 µm. Two types of plastic sheets, PC and PET, were tested in the laser cutting experiment.

Physical Characteristics of Particle Emissions during Laser Cutting

A scanning electron microscope (SEM), coupled with an energy dispersive spectrometer (EDS), was used to characterize the surface, structures and compositions of particles produced during the process of laser cutting. In addition, a particle counter (Lasair II) was utilized to investigate the size and number distributions of the particles emitted during laser cutting.

Odor Exposure Assessment

The odor exposure related to the laser cutting of plastics was investigated from three aspects. Firstly, air samples were collected at a close distance, 10 cm from the laser, operated at three controlled power levels (80 W, 160 W, and 240 W). The concentrations and gas-particle phase distributions of the odorous pollutants were measured. Each sampling duration was 15 min, with 3 samples and 1 field blank collected repeatedly.

Secondly, to assess the odor exposure of nearby employees who were assigned different jobs, air samples were collected at locations 1 m, 3 m, and 7 m away from the laser cutter. In addition, three samples, along with a field blank, were collected with a duration of 15 min, from the air in the neighboring connected clean room, for which the laser cutter would be the only possible source of air contaminants.

One meter represented the distance the operator was from the laser cutter, while distances of 3 m and 7 m respectively represented the locations of the neighboring co-workers doing material preparation and product inspection. The laser cutter was operated at 240 W, and a linear cutting speed of 15 m min^{-1}.

Thirdly, a protection efficiency test was performed to assess the effectiveness of using facial masks against the odorous emissions associated with the laser cutting of plastics. Four types of masks were selected for this study, including a non-woven fabric mask, an activated carbon mask, a regular N95 valved mask, and an activated carbon N95 valved mask. For phenols, 37-mm glass fiber filters were used to collect the emitted particles, while the XAD-7 resin was utilized for the gas phase sampling. For the measurement of carbonyls, DNPH-coated glass fiber filters were applied for particle phase samples, and DNPH-cartridges were used for gas phase samples. Additional samples were also collected at a distance of 1 m from the laser cutter for a period of 15 min. Finally, the protection efficiency of a local ventilation system against the odorous emission from the laser cutting of plastics was also assessed with the same air sampling conditions and methods.

Odor Analysis

Particle phase carbonyls were collected with DNPH-coated glass fiber filters (37 mm) at 3 L min^{-1}, and the filters were extracted using mechanical shaking for 30 min at room temperature with 5 mL of acetonitrile containing 0.02% pyridine. Gas phase carbonyls were collected by DNPH-cartridges at 0.5 L min^{-1}, followed by elution with 5 mL of acetonitrile. The extracted carbonyls were then analyzed with an HPLC system equipped with an auto-sampler and a diode-array UV/Vis detector (Thermo Scientific Dionex Ultimate®-3000) at 360 nm. The Supelco C_{18} column (250 mm × 4 .6 mm I.D., 5 µm) was used with the injection volume of 20 µL, a flow rate of 1 mL min^{-1}, using acetonitrile-water (50:50, v/v) as the mobile phase.

Particle phase phenols were collected by glass fiber filters (37 mm) at 3 L min^{-1}, which were extracted with mechanical shaking for 30 min at room temperature with 5 mL of methanol. Gas phase phenols were sampled by XAD-7 resin at 1 L min^{-1}, and extracted with mechanical shaking for 30 min at room temperature with 2 mL of methanol. The extracted min^{-1} phenols were then analyzed at the wavelength of 270 nm by the HPLC system. A Merck RP-C18 column (250 mm × 4.6 mm I.D., 5 µm) was applied with an injection volume of 20 µL. The mobile phase was

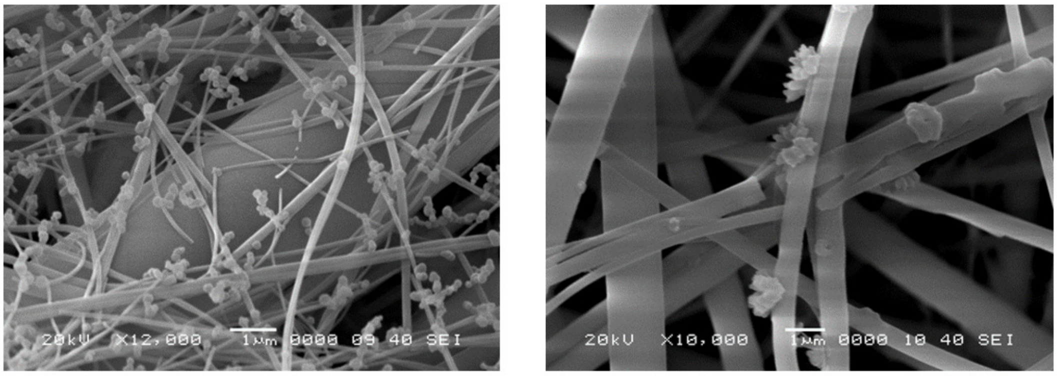
50% (v/v) aqueous acetonitrile, and the flow rate was 1 mL min^{-1}.

A field blank sample was collected during each sampling period to rule out any possible contamination of samples in the field and during the following transportation. Breakthrough experiments indicate that the breakthrough for all collected particle phase and gas phase samples were below 5%. The method detection limit (MDL) was also conducted for 15 carbonyls and 3 phenols. The MDLs were between 1.0 and 4.0 mg L^{-1}, and between 2.1 and 6.0 mg L^{-1}, for carbonyls and phenols respectively. The mean recoveries of these carbonyls and phenols were respectively 98.6% and 98.9% for products in the particle phase, and 91.1% and 89.9% in the gas phase.

RESULTS AND DISCUSSION

Particle Emissions from Laser Cutting

The fumes released during the process of laser cutting of PC were yellowish with a slight scorching smell, while PET cutting emitted white fumes with an irritating smell. Cenna and Mathew (2002) reported that energy absorption rate of materials could be affected by their thermal conductivities, which were 0.21 W m^{-1} K^{-1} and 0.29 W m^{-1} K^{-1}, respectively for PC and PET. In the present study, PC sheets were completely cut through using a 160 W laser, while only 80 W was needed for PET. In the present study, the particles collected on the glass fiber filters exhibited different microscopic structures. Fig. 1 shows that smaller, discrete, and spherical particles were found in the PC emissions, while larger and irregular particles were found in the PET emissions. The coefficients of water absorption and humidity for PET (0.5% and 0.25%, respectively) are higher than those of PC (0.4% and 0.15%), with wet and coagulated particles of PET, and dry powderous particles of PC, being observed during the process of laser cutting. The size distributions of PC and PET particles from laser cutting are shown in Fig. 2. At different power levels (80 W, 160 W, and 240 W), approximate 95%–97% of the particles were smaller than 1 µm. The particle numbers increased along with the laser power for the particle sizes of 0.5–3 µm for PC and 1–3 µm for PET. Despite studies indicate that the quantity, the composition, and the chemical complexity of the laser cutting generated air contaminants are highly



(A) Particles from laser cutting of PC (B) Particles from laser cutting of PET

Fig. 1. Particle structure of PC and PET at laser power 240 W.

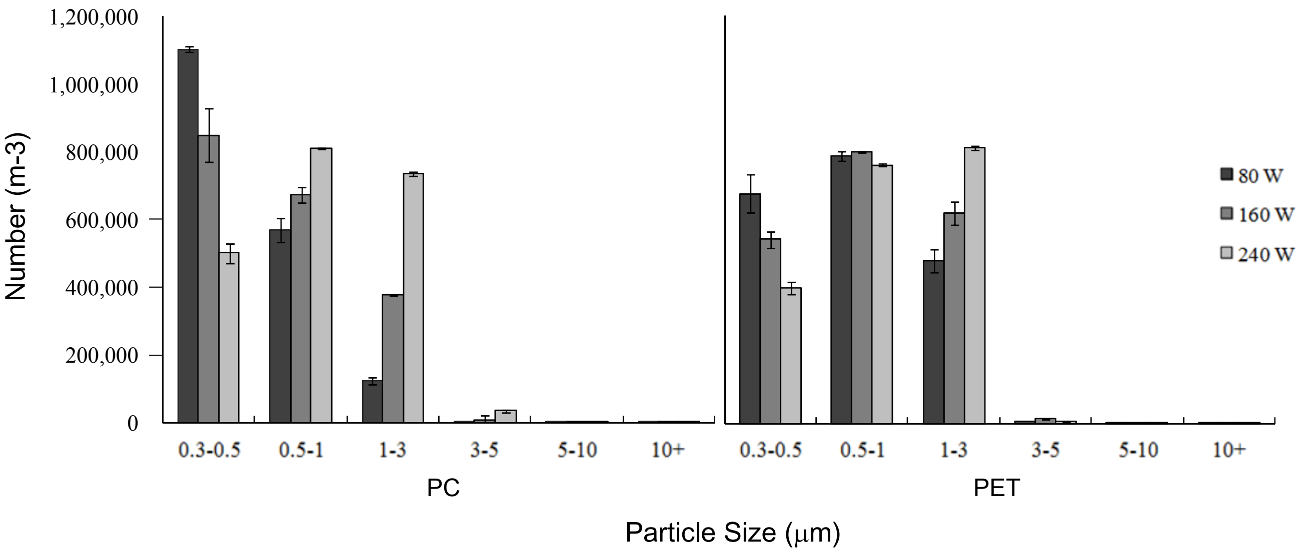


Fig. 2. Particle size distribution of PC and PET at different laser powers.

dependent on the laser application, the process parameters and the material processed (Haferkamp *et al*., 1998), the particles generated are mainly very fine and are therefore respirable. For instance, size distributions of aramid and expoxy from laser cutting (1000W) were mainly 0.12 µm–0.25 µm (Busch *et al*., 1989); size distributions of steel from laser cutting (10000W) were 81.3% of total dust < 0.52 µm (Tarroni *et al*., 1986); size distributions of biological tissue from laser cutting (30W) were mainly in the range of 0.54 µm–1 µm (Pierce *et al*., 2011). For some plastics, like polyamides, the fume particles are viscous and can easily stick together (Haferkamp *et al*., 1998).

However, the particle numbers decreased as the laser power rose for the particle sizes of 0.3–0.5 µm for both PC and PET. With regard to the particle size distribution less than 1 µm, 93.0%, 79.8% and 62% were detected from PC and 74.9%, 67.9% and 58.6% were detected from PET at laser powers of 80 W, 160 W and 240 W, respectively. As the laser power increased, the proportion of particles smaller than 1 µm decreased, while the total particle number concentrations of PC and PET at 80 W, 160 W and 240 W were held at the same levels, without any significant changes. This might be ascribed to the homogeneous nucleation that occurred with the smaller particles when using a higher power of laser (Leach *et al*., 1999; Takekawa *et al*., 2003).

Carbonyl Emissions from Laser Cutting

With regard to the carbonyls, nine of them were detected in the gas phase of the PC emissions, including formaldehyde, acetaldehyde, acetone, propionaldehyde, butyraldehyde, benzaldehyde, valeraldehyde, p-tolualdehyde, and hexaldehyde. Ten carbonyls were emitted from the laser cutting of PET, including formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, butyraldehyde, benzaldehyde, methyl butanal, p-tolualdehyde, and hexaldehyde. The total concentrations of the gas phase carbonyls reached a maximum at the laser cutting powers of 240 W (PC: 4.94 mg m^{-3}; PET: 14.0 mg m^{-3}) and a minimum at 80 W (PC: 1.89 mg m^{-3}; PET: 3.96 mg m^{-3}), as shown in Fig. 3. At each of the same laser powers, the total concentrations of the gas phase carbonyls of PET were all higher than those of PC. As for the particle phase carbonyls, formaldehyde, acetaldehyde, acetone, butyraldehyde, benzaldehyde, valeraldehyde, m-tolualdehyde, p-tolualdehyde, hexaldehyde, and 2,5-dimethylbenzaldehyde were found from PC, and formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, butyraldehyde, benzaldehyde, o-tolualdehyde, m-tolualdehyde, p-tolualdehyde, hexaldehyde, and 2,5-dimethylbenzaldehyde were detected from PET. Fig. 3 shows that in both the gas and particles phases, the total concentration of carbonyls increased with the increase of laser power. The total concentrations of particle phase carbonyls were highest during 240 W laser cutting (PC: 3.14 mg m^{-3}; PET: 6.54 mg m^{-3}), and the total concentrations of particle phase carbonyls seen with PET were higher those of PC at each of the same laser cutting powers.

Chemical compounds can be volatile or semi-volatile in the atmosphere in accordance with the length of their carbon chains, it is therefore possible for pollutants to exist in the environment as particle phase and gas phase contaminants simultaneously (Yang *et al*., 2007). In the present study, both particle phase and gas phase of carbonyls were detected. In Fig. 4, the results indicate that the total concentration of emitted carbonyls increased along with the power of the laser. Also, when cut at the same laser power, the emissions from PET, in both the gas phase and the particle phase, were respectively roughly two to three times of those from PC emissions. This might be ascribed to the fact that longer carbon chains are found in the structure of PET producing carbonyls composed of the chain of carbon, hydrogen, and oxygen. Carbonyls emitted from laser cutting process has been investigated, especially in biological tissue and surgical procedure (Lippert *et al*., 2014). However, relatively few studies had focused on this emerging application. In the optical industry, PC and PET are often in the flat and sheet form for laminating and converting to the optical products. Compare to PC, PET is a poor choice

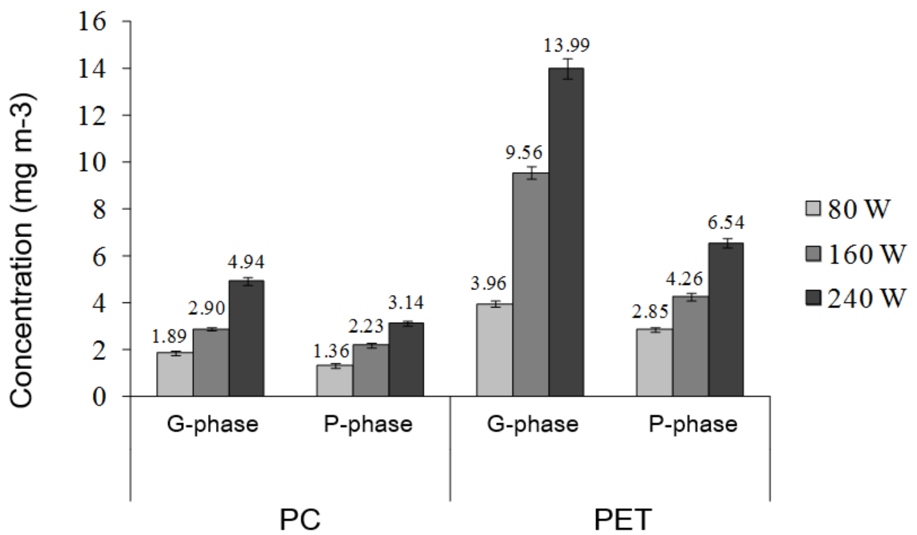


Fig. 3. The trends of the gas and particle phases of carbonyls of PC and PET at different laser powers.

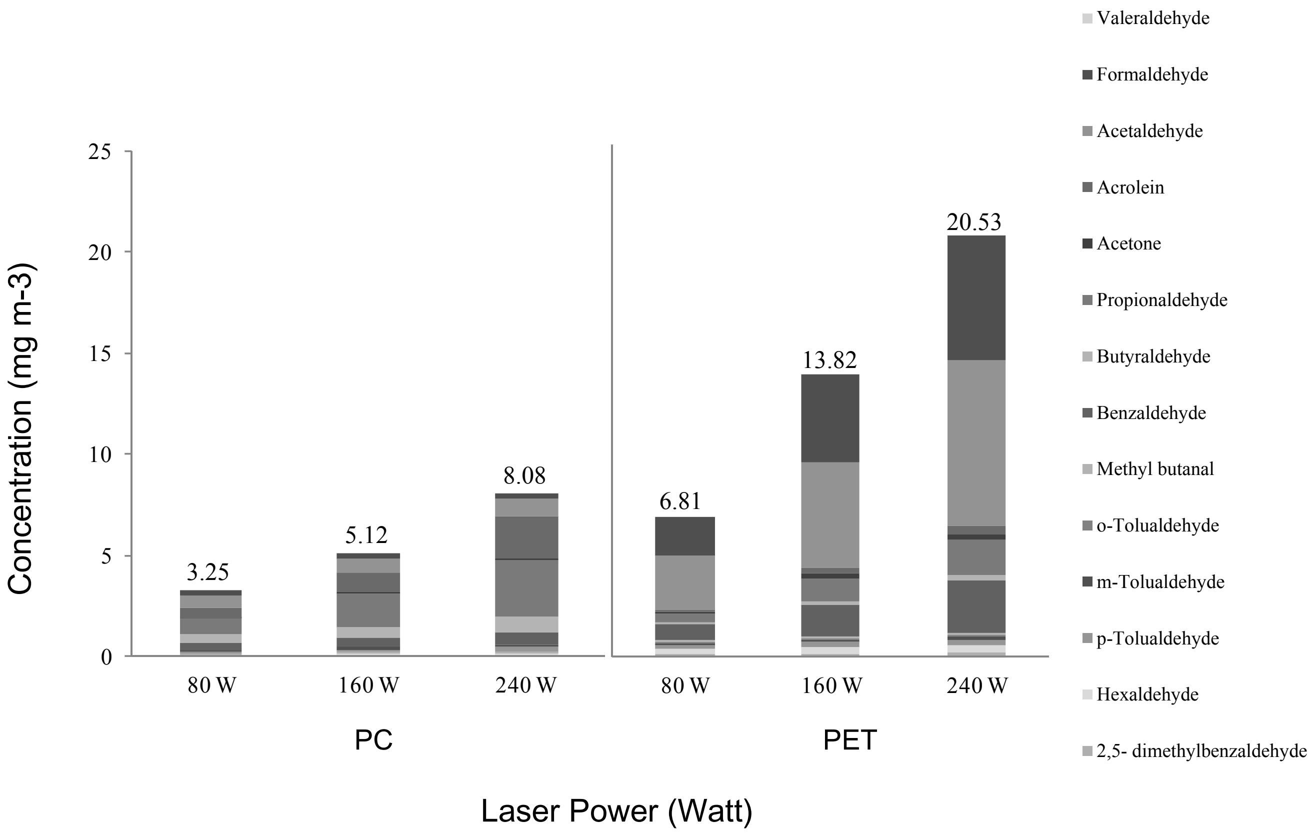


Fig. 4. Total carbonyl concentrations of PC and PET at different laser powers.

for laser cutting because of higher carbonyls emission during laser cutting, which contained higher level of odorous substances and carcinogens, such as formaldehyde.

Phenol Emissions from Laser Cutting

Three different phenols, including phenol, o-cresol, and m+p-cresolnine, were detected in both the gas and particle phases of the emissions of PC and PET during laser cutting. With regard to phenol generated from laser cutting process, there has been no quantitative study reported. A qualitative study indicated the phenol and cresol could be detected during PC and PET cutting by laser (Sims *et al*., 1993). Plasticizer Bisphenol A (BPA) is often employed for making PC and PET films to make the materials and products clean and tough. At high temperatures, BPA are mainly destroyed, generating phenols as the degradation products (Grause1 *et al*., 2010). The phenols detected in the present study might be ascribed to the thermal degradation of BPA at high laser temperatures. The present study show that their total concentrations were the highest at the laser cutting power of 240 W for PC (gas phase: 0.87 mg m^{-3}; particle phase: 0.69 mg m^{-3}), and the lowest at 80 W for PET (gas phase: 0.43 mg m^{-3}; particle phase: 0.36 mg m^{-3}), as shown in Fig. 5. The total concentrations of phenols in both phase from PC were slightly higher than those from PET at each of the same laser cutting powers. Fig. 6 shows that total concentrations of all phenols emitted from the cutting of plastics increased along with the laser power. Also, at each laser power level higher total concentrations of phenols were observed in PC emission than those from PET. This might be ascribed to the two-benzene ring monomeric structure in PC, which possibly produced more benzene-ring-containing phenols molecules than PET, which has only one benzene ring in this monomeric structure.

Assessment of Worker Exposure to Carbonyls and Phenols

Many studies have demonstrated that laser-generated air contaminants (LGACs) may contain noxious and toxic aerosols, gases, vapors, or fumes generated from laser cutting or laser engraving. Effective exposure controls and proper protections are always recommended for airborne pollution that workers are exposed to in the workplace (Chen *et al*., 2015). Despite very few studies have attempted to characterize the effects of laser system type, power level, the adverse health risks to laser operators is anticipated (Pierce *et al*., 2011). Occupational exposure levels of LGAC to the laser operators can certainly exceed occupational exposure limit (OEL). Laser operators often complained about their eye and skin irritations as well as the smelly odor, as reported by Tharr (1991). With regard to the worker exposure assessment in the present study, those who were working at the closest proximity to the machine (1 m from the laser cutting) were exposed to the highest concentrations of odorous emissions of PC (carbonyls: 3.82 mg m^{-3}; phenols: 1.00 mg m^{-3}) and PET (carbonyls: 9.22 mg m^{-3}; phenols: 0.83 mg m^{-3}); whereas the product inspectors (7 m away from the cutting site) were exposed to the lowest

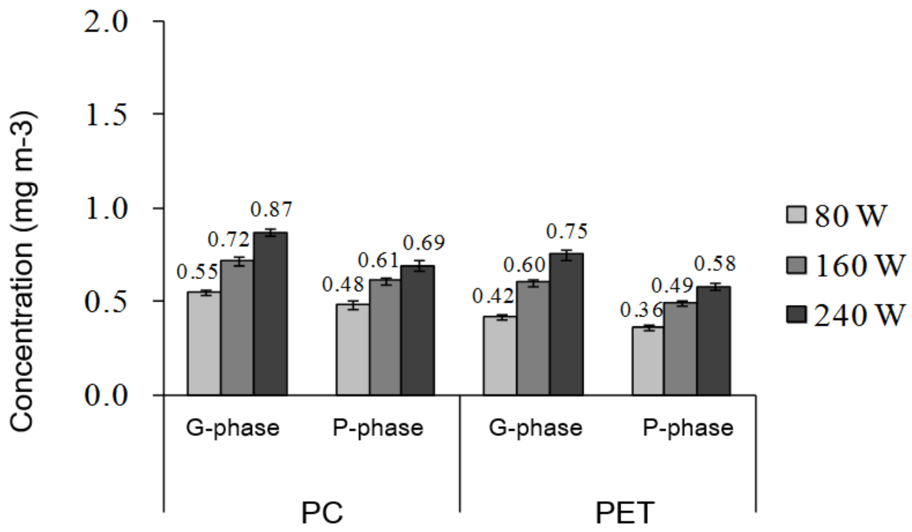


Fig. 5. The trends of the gas and particle phases of phenols of PC and PET at different laser powers.

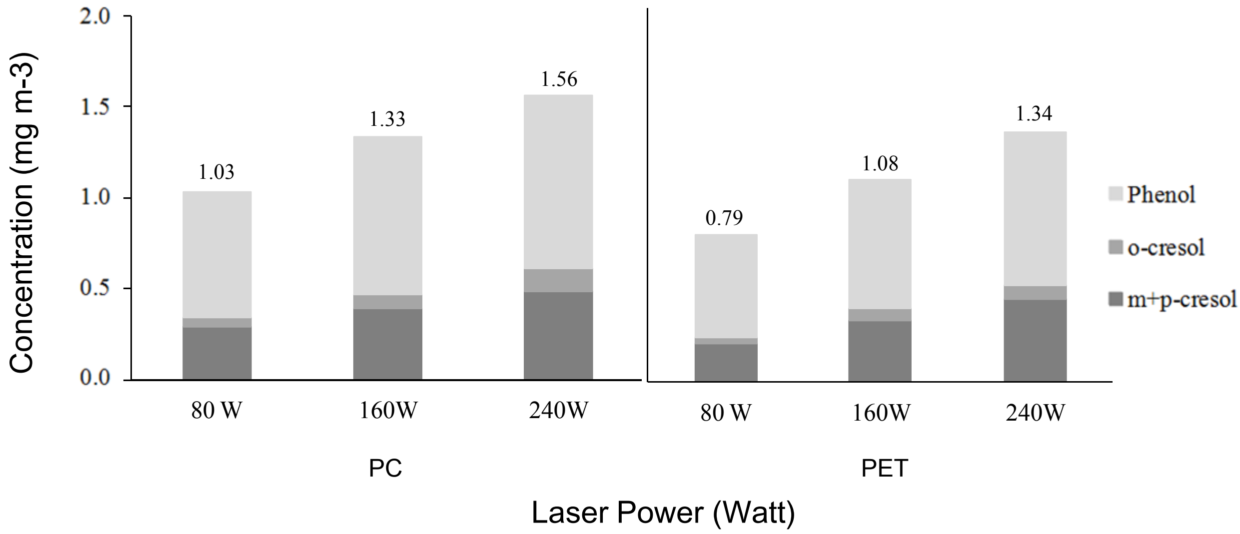


Fig. 6. Total phenol concentrations of PC and PET at different laser powers.

concentrations of PC (carbonyls: 0.17 mg m^{-3}; phenols: 0.03 mg m^{-3}) and PET (carbonyls: 0.80 mg m^{-3}; phenols: 0.02 mg m^{-3}), as shown in Figs. 7 and 8.

The results indicate the difference of carbonyl emission profiles between laser cutting on PC and PET were identified. For PC laser cutting, the highest concentration was butyraldehyde, then acetone and acetaldehyde. For PET laser cutting, the highest concentration was acetaldehyde, then formaldehyde and propionaldehyde. In the present study on laser cutting PET, the carcinogen, formaldehyde, exposure of the laser cutter operators was 2.68 mg m^{-3}, which exceeded the Permissible Exposure Limit-Short Term Exposure Limit (PEL-STEL) of 2.4 mg m^{-3}, a value recommended by the Occupational Safety and Health Administration (OSHA). With regard to the phenol emission profiles between laser cutting on PC and PET, the highest concentration was phenol, then m- + p-cresol and o-cresol identically.

The gaseous fraction of the odorous substances increased from between 58.1% and 75.4% at a distance of 1 m to between 96.9% and 100% at a distance of 7 m, as shown in Fig. 9. This is because that gaseous compounds, being smaller molecules, diffuse faster than particles. The results indicate that workers directly engaged in operating a laser cutter were exposed to higher levels of odorous substances as well as hazardous air contaminants than those working on the nearby material preparation station or product inspection station. Individuals working further away from the laser cutter were exposed to lower levels of pollution. The results also indicate that comparing to the laser cutter operator, the higher proportion of gas phase carbonyls and phenols exposure to the material preparation workers were observed. This might be ascribed to the gas phase contaminants can be easily dispersed in the air by the gradient of concentration and air flow. Despite those stationary samples were collected at each work station (30 cm distance from the laser cutter operators, material preparation workers and product inspectors, respectively) to simulate

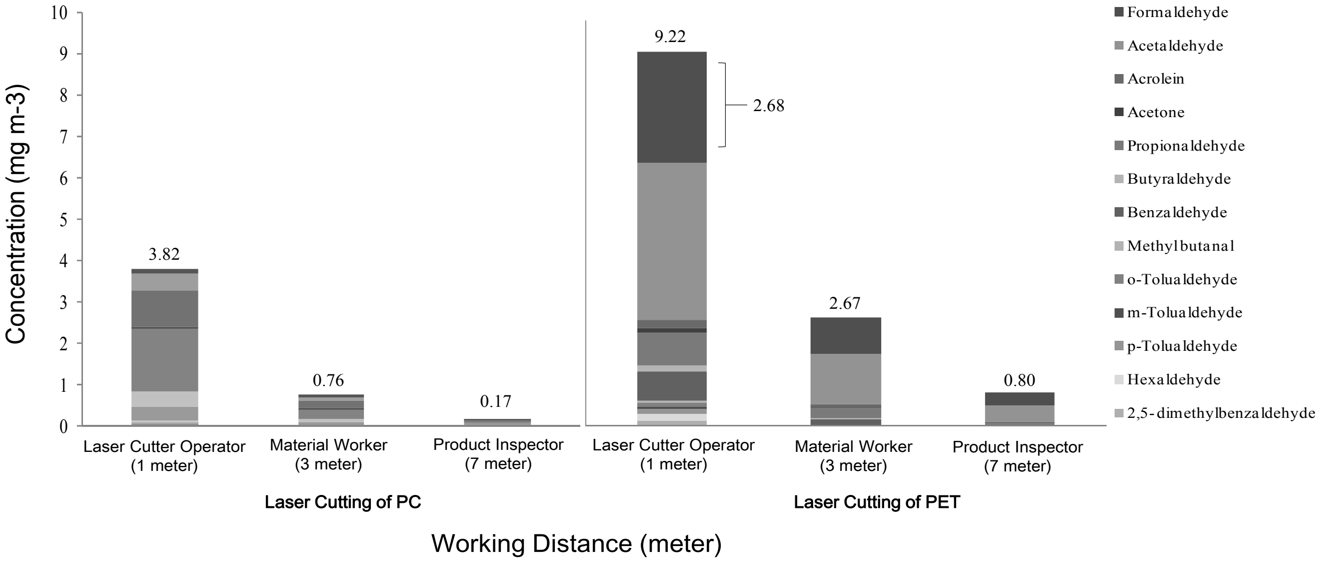


Fig. 7. Total carbonyl concentrations of PC and PET at different exposure distances.

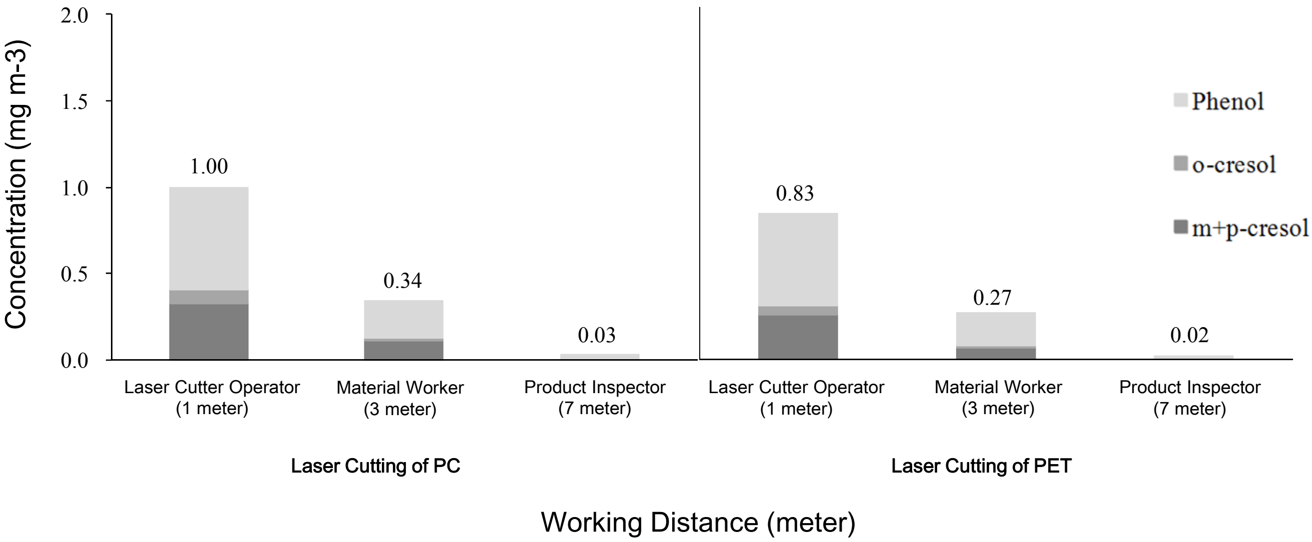


Fig. 8. Total phenol concentrations of PC and PET at different exposure distances.

personal odorous substances exposure, the breathing zone sampling of the laser cutter operators, material preparation workers and product inspectors were also considered for representativeness compliance.

Efficiency Test for Protection against Exposure to Odorous Emissions during Laser Cutting

Practically, there are two approaches to protect operators against the LGAC exposure — the use of ventilation and respiratory protection. Ventilation protection, which is the most important, can provide protection by directly and actively removing the hazardous and odorous air contaminants from the site. Respiratory protection, on the other hand, provides a passive protection by intercepting or capturing the air contaminants. The study result from Howard (2011) indicated the workers in the laser operating area are potentially facing a high risk to airborne contaminants if the protection is inadequate. The results of the present study showed that laser cutting of PC and PET generated high levels of phenols and carbonyls, respectively. The phenols from PC and carbonyls from PET laser cutting were used as the target pollutants to assess protection efficiency of selected facial masks. The source samples (10 cm from the laser) were used as baseline concentrations for the comparison of protection efficiency of the masks. A sampling train simulating a human face wearing a well-sealed mask/respirator was designed to imitate the condition of workers wearing respirators as a protection measure. The results for the four masks in terms of their filtration efficiency for odor substances were as follows: N95 valved active carbon respirator > ordinary N95 valved respirator > activated carbon mask > non-woven fabric mask (Figs. 10 and 11). The total concentrations of carbonyls were 0.31 mg m^{-3} for the N95 valved active carbon respirator, 4.55

mg m^{-3} for the ordinary N95 valved respirator, 5.15 mg m^{-3} for the activated carbon mask, 6.49 mg m^{-3} for the non-woven fabric mask, and 9.24 mg m^{-3} for no mask. The total concentrations of phenols were 0.03 mg m^{-3} for the N95 valved active carbon respirator, 0.38 mg m^{-3} for the ordinary N95 valved respirator, 0.57 mg m^{-3} for the activated

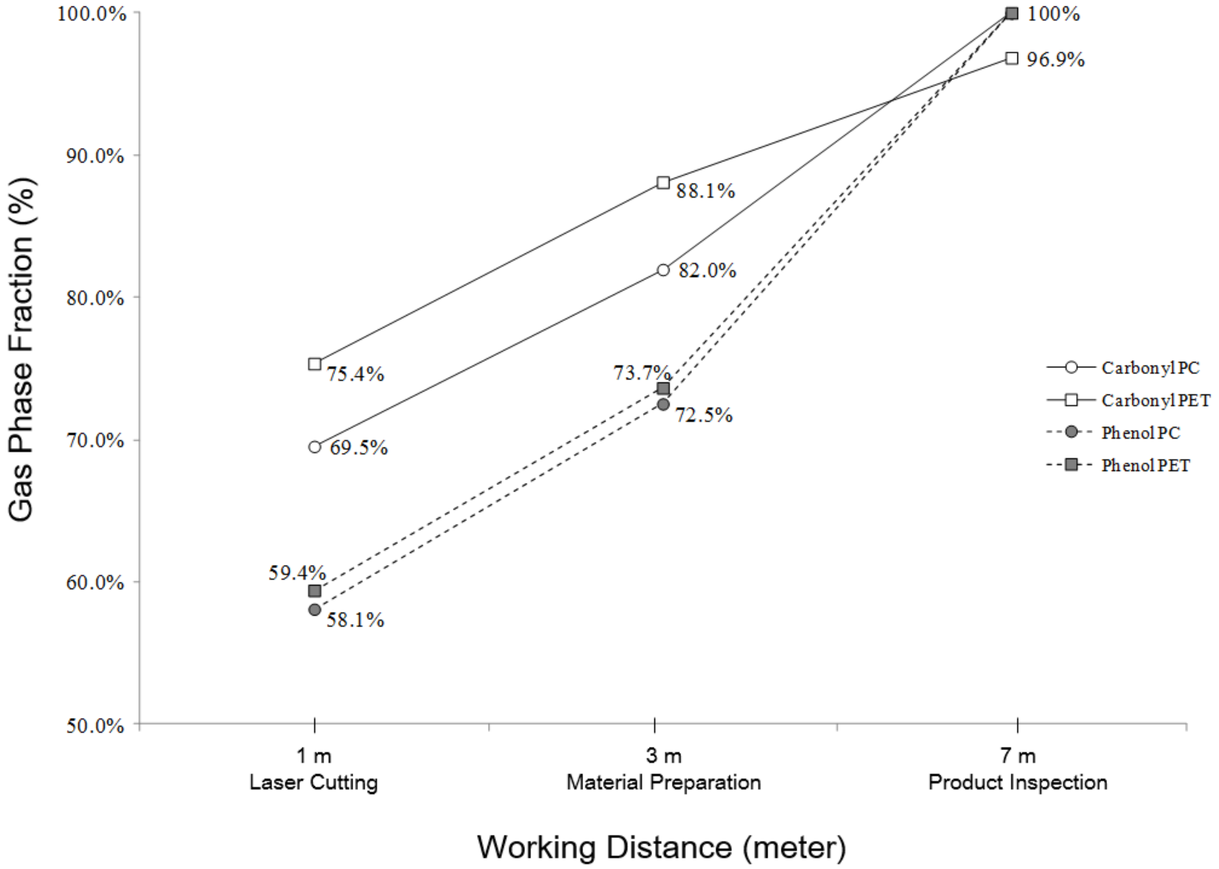


Fig. 9. Total phenol concentrations of PC and PET at different exposure distances.

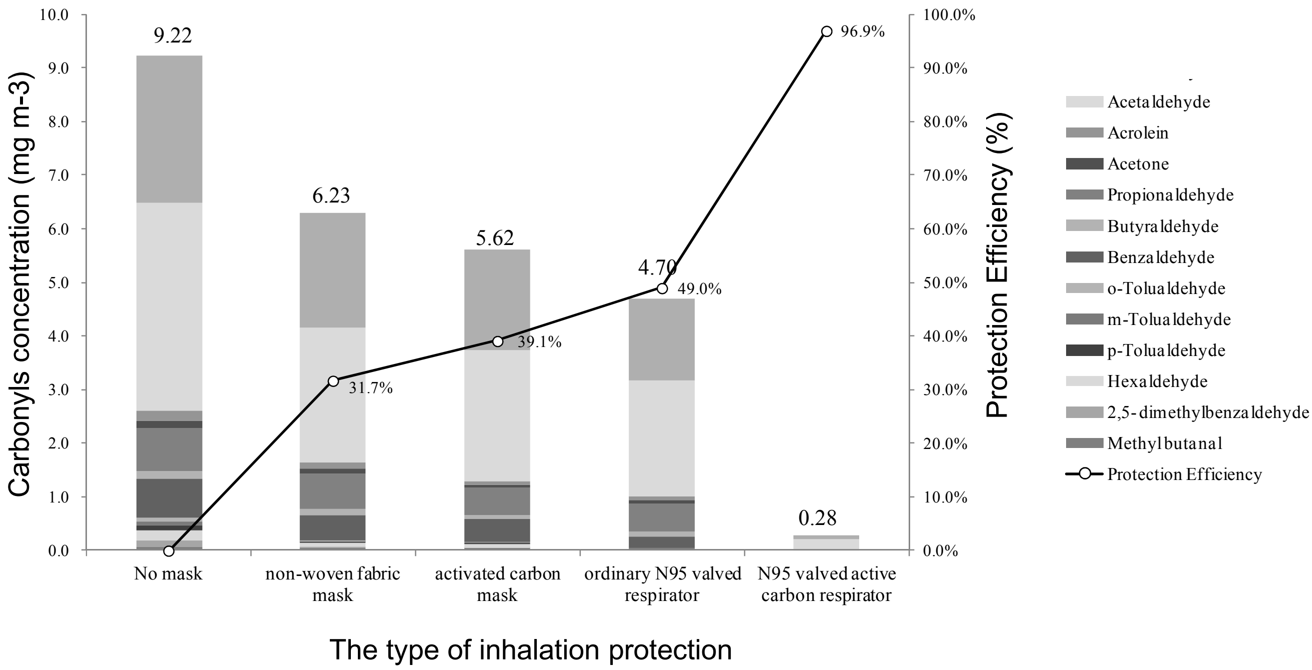


Fig. 10. Total carbonyl concentrations with different masks during laser cutting of PET.

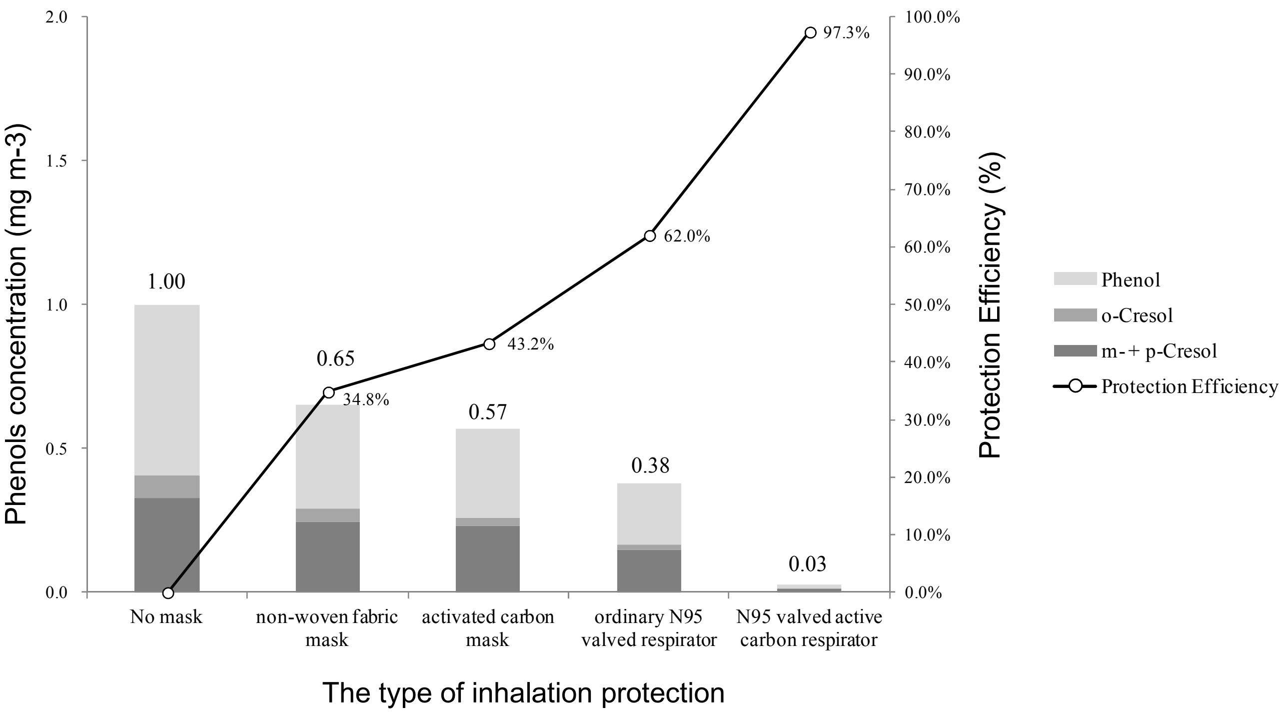


Fig. 11. Total phenol concentrations for different masks during laser cutting of PC.

carbon mask, 0.65 mg m^{-3} for the non-woven fabric mask, and 1.03 mg m^{-3} for no mask. With regard to the filtration mechanism, the particle phase air pollutants, from particular to very fine particles (e.g., nanoparticle), can be captured by electrostatic mechanism of N95 respirator (Samy *et al.*, 2009). Zou and Yao (2015) stated that the respirator masks could achieve a practical protection efficiency higher than 90%, while N95 types could obtain more than 99% absolute protection efficiency under fully sealed conditions. With regard to the odor exposure elimination, a respirator filled with activated carbon could effectively remove noxious gases and vapors from a contaminated air stream, as verified by Harry and Francisco (2006). The N95 valved active carbon respirator had the best removal efficiency for the gas/particle phases of carbonyls and phenols compared to other types of masks, and is therefore the best mask to protect workers from exposure to odorous substances during the laser cutting of plastics. Fitting test on wearing the respirator is critical since the protection efficiency also depends on how tight the mask seals the face. An optimal protection efficiency can be achieved only when a perfect fitting is assured, and the respirator life cycle is well-managed.

For the ventilation protection assessment, the samplings were conducted at 240 W, the highest laser cutting power, to study the carbonyls emission from PET and the phenols from PC. Also, source samples were selected as the baseline concentrations for the ventilation protection evaluation. It is generally recognized that dilution ventilation is insufficient to effectively control smoke generated at the laser cutting site (Pierce *et al.*, 2011). In order to study the effect of ventilation on the emission, a local exhaust ventilation (pull-push type) was installed in the current study to assess the reductions of pollutants in both the gas and particle phases in the working environment. The results showed that no particle phase carbonyls were detected and only gas phase formaldehyde and acetaldehyde were detectable during laser cutting of PET with the local ventilation turned on (Fig. 12). On the other hand, phenols were only detected in the gas phase, not in the particle phase during laser cutting of PC with the local ventilation on (Fig. 13). Even better than using a N95 valved active carbon respirator, the most effective way to reduce the exposure to odorous emissions found in this study was the installation of a local ventilation with an enclosing hood positioned directly above the laser cutting machine, which can effectively remove all emitted odorous particulate matter and reduce the concentration of gaseous odorous substances in the working environment by 99%.

CONCLUSIONS

The odorous gases generated during laser cutting of plastics are known to be harmful to workers. Characterization of the emission products offers helps in optimizing the laser power and reducing the amount of pollutants being produced. For ultimate prevention against production of harmful air pollutants during laser cutting, safer materials should be sought and/or effective protection measures be taken to protect the health of the workers.

Our results indicate that the pollutants released during laser cutting of PET are very harmful, suggesting that PC be more preferable as the primary base material for optical films. We also recommend that workers wear N95 valved active carbon respirators and/or a local ventilation be installed above laser cutting machines.

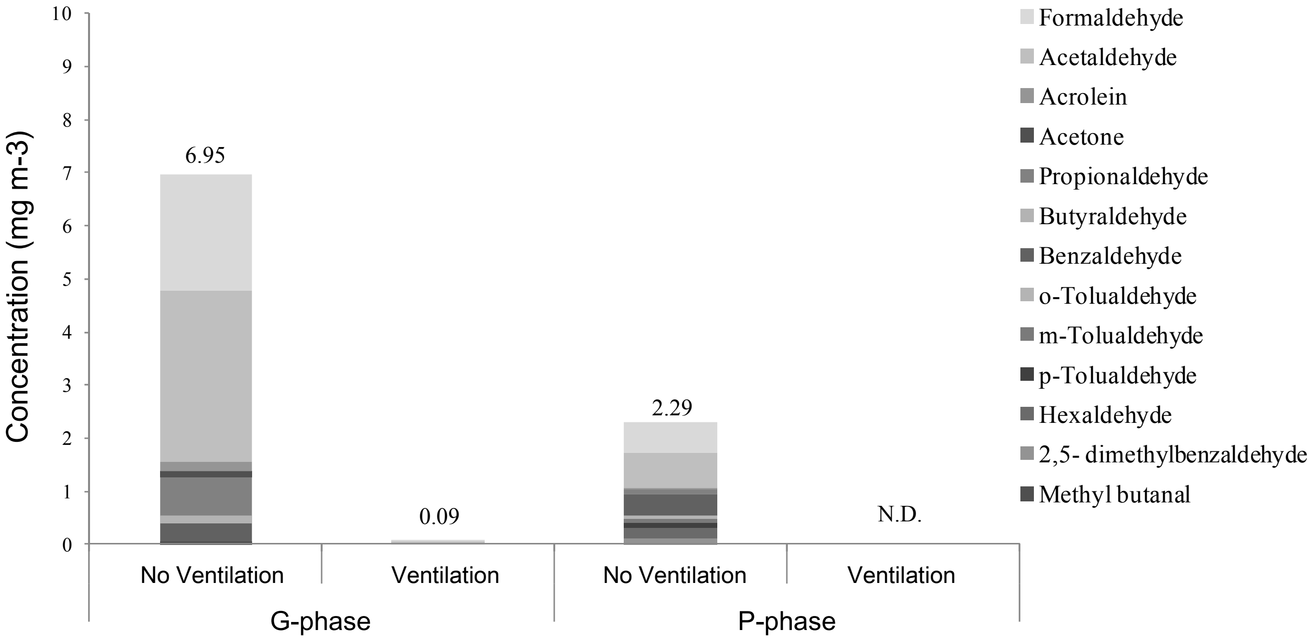


Fig. 12. Total carbonyl concentrations at different ventilation conditions during laser cutting of PET.

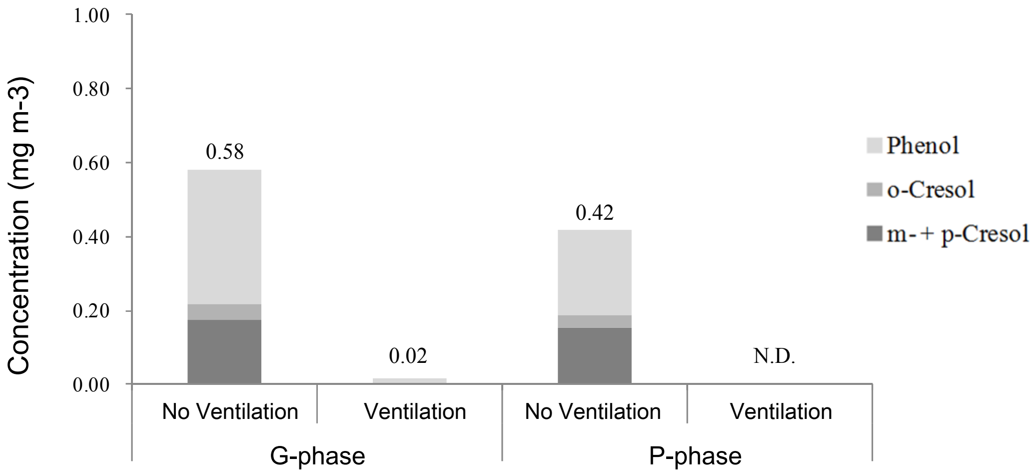


Fig. 13. Total phenol concentrations at different ventilation conditions during laser cutting of PC.

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