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Oil mist collection and oil mist-to-gas conversion via dielectric barrier discharge at atmospheric pressure

Sang Shin Park, Myung Soo Kang, Jungho Hwang [*]

Department of Mechanical Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea

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ABSTRACT

A dielectric barrier discharge (DBD) reactor was fabricated and operated in two steps. In the first step (oil mist collection) oil mist aerosols were collected and in the second step (oil mist-to-gas conversion), without supplying oil mist particles but with supplying only clean air flow, collected oil mist particles were converted to gas species. An aerodynamic particle sizer, a scanning mobility particle sizer system, and a real-time gas analyzer were used to measure particle and gas concentrations at the inlet and outlet of the DBD reactor. The oil mist collection efficiency decreased from 78% to 21% but the oil mist-to-gas conversion efficiency increased from 6% to 95%, with increasing frequency from 1 kHz to 10 kHz. Low frequency caused higher amplitude of oscillating particle movement between the electrodes, resulting in higher collection efficiency. At a higher frequency, more electrons were generated, which resulted in the formation of more reactive oxygen species and thus increased subsequent oxidation. Increased surface temperature of the DBD reactor with higher frequency also contributed to higher oil mist-to-gas conversion efficiency. The DBD reactor can be applied to reduce oil mists generated in metal working and cooking processes.

1. Introduction

Oil mist is generated by the application of the metalworking fluid, by the interaction of the cutting tool, work piece, and fluid, and by evaporation and condensation processes associated with heat generated as machining takes place [1,2]. Oil mist is also generated by stir-frying or deep-frying food in oil, or preheating oil prior to the addition of food and these cooking processes [3]. These mists pose a risk to both the environment and to human health and therefore need to be treated [4]. Inhalation and dermal exposures to oil mist, their additives, and the contaminants from the metal machining process have been associated with adverse health effects [5].

Oil mist is emitted as aerosols in the size range of about 0.1–1 μm [6]. Occupational Safety and Health Administration (OSHA) has set the permissible exposure limit of 5 mg/m^3 for mineral oil mist in air, averaged over an 8-h period [7]. However, the Environmental Protection Agency (EPA) due to the importance of particle size, has changed the focus of its particulate standards from total airborne particles to particulate matter (PM) less than 10 μm (PM10) and less than 2.5 μm (PM2.5) [8]. The shift toward regulating smaller particles is related to their longer residence time in air, their usually more active chemistry, and their deeper penetration into the respiratory system [7,9]. Considering mineral oils are produced by petroleum distillation processes, semi-volatile organic compounds, such as polycyclic aromatic hydrocarbons (PAHs), are expected to be contained in emitted oil mists [10]. Several carcinogens, including polycyclic aromatic hydrocarbons (PAHs), aromatic amines and nitro-polycyclic aromatic hydrocarbons, which are also found in cigarette smoke, can be found in the fumes from cooking oil and appear in the kitchens of Asian homes where women prepare food daily [11].

The removal of oil mists from air streams is important in many industrial applications, such as machining and cutting operations, engine closed crankcase ventilation, and compressed gas cleaning. Sokolovic et al. [12] carried out an experimental study of aerosol/mist formed from emulsions of three different commercial metalworking fluids under laboratory conditions. The data for aerosol size distribution, Sauter mean diameter, mass median diameter, and mass concentration are reported and discussed. Oil mist emitted by cooking process has been also reported to increase the risk of lung cancer in oriental women because of exposure to mutagenic substances present in the cooking fume [13]. Shields et al. [14] measured different pollutants emitted from cooking foods in relation to various appliances such as ovens, broilers,

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[*] Corresponding author.
E-mail address: hwangjh@yonsei.ac.kr (J. Hwang).

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and griddles. They found the highest levels of emissions from fatty foods cooked at high heat, especially over open flames. The Seoul City Council [15] and the Gyeonggi-do Province Council [16] in Republic of Korea issued municipal ordinances for control facility installation of oil mist emitted by cooking process.

There are several oil mist reduction methods: local ventilation, filtration, catalytic/thermal oxidation, and non-thermal plasma technique. For the local ventilation method, Sokolović et al. [17] studied the effect of ventilation with various air velocities of 1, 3, 6, and 8 m/s for metalworking fluids (MWFs) aerosol/mist, which was generated from 6% water emulsion of three commercial MWFs. Rim et al. [18] evaluated reduction of cooking emitted ultra-fine particle with a kitchen exhaust hood. They considered three different parameters of exhaust hood flow rate, particle size, and burner position. For the filtration method, Gilmer et al. [19] investigated microfiltration characteristics of a synthetic metalworking fluid and discussed the impact of contaminants on membrane flux. Hepner [20] invented an improved filtration system for a commercial cooking stove, which eliminates grease, particles and odors from exhaust air of the stove through a regenerative charcoal filter and returns the filtered air to the room. For the catalytic/thermal oxidation method, García-Jarana et al. [21] employed KOH catalyst to treat cutting oil generated from metalworking process in supercritical water gasification at a temperature of 450 °C and a pressure of 2.5×10^7 Pa. Yang et al. [22] employed low temperature catalytic oxidation to treat cooking oil fume. They developed a novel catalyst based on MnO_2/CuO and studied catalytic under different oil temperatures, catalyst temperatures and contact times. Sánchez-Oneto et al. [23] studied the application of hydrothermal oxidation in supercritical conditions to treat two semi-synthetic cutting oil fluids under temperatures ranged from 300 to 500 °C and pressure of 25 ± 0.3 MPa. Wang et al. [24] carried out catalytic combustion experiment of cooking fume in a conventional fixed-bed flow reactor using four monolithic catalysts with low concentration of noble metal.

The local ventilation is most widely used, however, it requires high energy consumption and easily produces secondary pollution, and the corresponding equipment needs large area for installation [25–28]. Most efficient filters with high packing densities often cause high pressure drop that can increase over time due to additional loading [29,30]. The catalysis is important in the removal of organic wastes from gaseous effluents, as oxidation to carbon oxides and water can be achieved at suitably low temperatures (200–600 °C) [31]. However, using catalyst requires expensive operation cost and periodic replacement (or catalytic regeneration) due to catalytic poison. Thermal oxidation (combustion) also requires expensive equipment, high operating and maintenance cost and production of NO_x will offset the benefits of organics removal [24].

Especially, a non-thermal plasma method has been considered for air purification systems to remove trace contaminants by converting them to less harmful species through reactions in a plasma reactor. In non-thermal plasma, free electrons gain energy from an imposed electric field and lose energy through collisions with neutral gas molecules. This transfer of energy leads to the formation of a variety of new species, including ions, metastable species, atoms, and free radicals. The most distinctive characteristic of non-thermal plasma is its ability to induce various chemical reactions [32,33].

Among the non-thermal plasma methods, an electrostatic precipitator (ESP) and dielectric barrier discharge (DBD) are important techniques. The ESPs are commonly used for particle removal. They can handle large gas volumes and collect a wide range of particle sizes without draft loss [34]. Yansheng et al. [35] carried out experiment of purifying of welding fume using the spot with corona plasma. The relationship between the corona discharge voltage and the purifying efficiency was investigated with different needle-electrode numbers, different ring-electrode numbers, and different needle-plate distances. Chen et al. [36] studied the removal of hexanal (one of main components in cooking oil fume) using a combination of a non-thermal plasma and catalyst in one reactor (the catalyst was placed in the discharge area of the dielectric barrier discharge plasma) and at 80 °C, which is close to the gas temperature of cooking oil fumes. Despite their effectiveness, ESPs have limitations including high capital costs, large space requirements, and lack of flexibility once installed [37]. Furthermore, some ESPs inherently generate ozone and indoor secondary particles [38,39]. The dielectric barrier discharge (DBD) has been of interest because it has higher efficiency in generating gas-phase radicals compared to other non-thermal plasma methods, such as corona discharge plasma [40]. The plasma density of DBD is 10^{12}–10^{15} ions/cm^3, which is much higher than that of corona plasma, 10^9–10^{13} ions/cm^3 [41]. DBD has been studied for reduction of hazardous materials [32, 42–47]. Byeon et al. [32] studied removal of gaseous toluene and submicron-sized aerosol particles in a lab-scale DBD reactor. Kim [42] studied and reviewed environmental application of non-thermal plasma, for example as an air-pollution control system, for sterilization, and for water treatment. Roland et al. [43] examined the performance of a DBD reactor in removing organic air pollutants (especially in low concentrations) by introducing ferroelectric and catalytically active materials into the DBD zone. Seto et al. [44] developed a micro-scale-patterned electrode surface DBD reactor to decompose volatile organic compounds. Borra [45] briefly reviewed the fundamentals and various applications of DBD reactors, including nano-particle and aerosol control. Park et al. [46] attempted to simultaneously remove odors, airborne particles, and bio-aerosols from a municipal composting facility using a DBD reactor. Jidenko and Borra [47] carried out experiments for diethylhexyl-sebacate (DEHS) removal using lab-scale self-cleaning filters based on a DBD reactor in air at atmospheric pressure. They used a low frequency (1 kHz) for electro-collection and a high frequency (60 kHz) for filter cleaning.

In this study, a dielectric barrier discharge (DBD) reactor was fabricated and operated in two steps. In the first step (oil mist collection) oil mist aerosols were collected and in the second step (oil mist-to-gas conversion), without supplying oil mist particles but with supplying only clean air flow, collected oil mist particles were converted to gas species. For this purpose, an aerodynamic particle sizer (APS), a scanning mobility particle sizer (SMPS), and a real-time gas analyzer were used to measure particle and gas concentrations at the inlet and outlet of the DBD reactor across a wide frequency range (1–60 kHz).

2. Experimental set-up and method

As shown in Fig. 1, the experimental apparatus consisted of a clean air supply system, oil mist aerosol generator (Condensation monodisperse aerosol generator; CMAG 3475, TSI, USA), DBD reactor, and measurement instruments. The clean air was generated with compressed air passing through an oil trap (Oil Trap 1271988, URO, USA), pressure regulator (GPR 1000, Hiflux, Korea), diffusion dryer (DIFFUSION DRYER 3062, TSI, USA), and high-efficiency particulate air filter (HEPA 244-filter, Nanjing Blue Sky Filter, China). The clean air was then supplied to the oil mist aerosol generator at a flow rate of 3 L/min. Another stream of clean air was delivered through the acrylic duct (height, width, and length: 5 cm × 5 cm × 70 cm) at a flow rate of 7 L/min and mixed with the air carrying oil mist aerosols. In the previous study of Byeon et al. [32], they used residence time of about 0.1 s in their DBD reactor. In this study, the residence time was also chosen as 0.1 s with the flow rate of 7 L/min (the discharge volume in the