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Impact of design parameters on the performance of non-thermal plasma air purification system

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HIGHLIGHTS

- Effect of different design parameters on the system performance are investigated.
- Energy consumption and the rate of ozone generation of a DBD plasma are optimized.
- Ground electrode configuration is a dominant parameter on ozone generation not its type.
- Larger inner electrode results in an earlier plasma ignition and higher ozone amount for the same SIE.
- Increasing the reactor size requires larger SIE amounts to reach the same ozone level.

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ABSTRACT

In this study, a dielectric barrier discharge (DBD) non-thermal plasma experimental set-up is utilized to investigate the effect of design parameters including the configuration and type of electrodes as well as the size of the reactor on the energy consumption and the rate of ozone generation. Results show that increasing the residence time by applying a larger length of the inner electrode causes an earlier plasma ignition, as well as formation of larger amounts of ozone for a given specific input energy (SIE). Changing the configuration and the type of the ground electrode shows that this electrode configuration is a dominant parameter for enhancing the energy yield in the plasma reactor. Furthermore, it was noted as the size of the reactor is increased, by increasing the gap between the electrodes, higher level of SIE is needed to reach the same level of ozone concentration.

1. Introduction

Over the past decade, non-thermal plasma (NTP) systems have been considered as indoor air treatment methods for removal of volatile organic compounds (VOCs) [1–4], as well as particulate matters [5,6] and bacteria [7,8]. In this method, acceleration of electrons takes place in the presence of a high voltage discharge. The collision of these high energy electrons with the molecules in the air causes the formation of different types of reactive species, ions and radicals (R^*, R^+, R^-), which contribute to oxidation reactions of organic pollutants as well as removal of particulate matters and bacteria [1,9].

The advantages of NTP systems include destruction of VOCs for a wide range of concentration, especially concentrations lower than 100 ppm [10], and also their relatively high removal efficiency for particulate matters [5,6]. However, there are some concerns, which restrict the application of these systems for the indoor environment. One of these concerns is related to the high level of energy consumption in plasma-based systems [9,11]. To overcome this problem, different types of plasma systems have been studied for utilization in indoor environment [9,12]. Among them, dielectric barrier discharge (DBD) systems have attracted significant attention due to their facile implementation and scale up, and higher energy efficiency [13,14]. A DBD reactor consists of one or two dielectric barriers between the two electrodes. The discharge which is initiated on the surface of the inner electrode produces large volume of micro-discharges [15,16]. The characteristics of

Abbreviations: AC, alternating current; DBD, dielectric barrier discharge; DE, dielectric; GE, ground electrode; HV, high voltage; IE, inner electrode; NTP, non-thermal plasma; ppm, part per million; SD, standard deviation; SIE, specific input energy; VOC, volatile organic compound.

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micro-discharges depend on different parameters including reactor configuration, composition of the gap–gas, as well as its pressure, the field polarity, and the frequency of the applied voltage [16].

The second and very important concern of plasma-based method is formation of large amounts of ozone molecules as one of the reactive species [17,18]. Formation of ozone is a consequence of dissociation of oxygen and nitrogen molecules [14]. The main part of the ozone formation is the result of a reaction, which takes place in a few microseconds, in the presence of micro-discharges in a DBD system, as follows:

$$O + O_2 + M \rightarrow O_3^* + M \rightarrow O_3 + M \quad (1)$$

M is described as a third collision partner including O_2, O_3, O or N_2 in the case of air [14]. In addition, dissociation of nitrogen molecules in the air initiates a series of reactions that eventuates to generation of more O_3 molecules due to the formation of oxygen atoms [14] according to the reactions (2)–(5):

$$N + O_2 \rightarrow NO + O \quad (2)$$

$$N + NO \rightarrow N_2 + O \quad (3)$$

$$N_2(A) + O_2 \rightarrow N_2O + O \quad (4)$$

$$N_2(A, B) + O_2 \rightarrow N_2 + 2O \quad (5)$$

The presence of large volumes of ozone in the treatment of drinking water or flue gas with high concentration levels of pollutants is an advantage, as it can play a significant role in the decomposition of pollutants [17,19]. Yet, when it comes to its application for indoor air treatment, due to very low concentration levels of VOCs, generation of high amounts of ozone is not necessary. In addition, this highly reactive molecule has been recognized as a hazardous compound for occupants' health [20–22]. One approach to reduce the ozone concentration is introducing a catalyst downstream of the plasma reactor [23]. The catalyst not only removes the residual ozone from the downstream, but also initiates a series of heterogeneous catalytic reactions in the presence of the ozone which eventually results in enhancement of VOCs removal performance [1].

Several studies have reported destruction of VOCs with concentrations around two ppm successfully using the ozone level of less than 60 ppm in the presence of a catalyst [3,24]. For instance, while the removal efficiency of 2.2 ppm formaldehyde in a NTP reactor was 36%, utilizing MnO_x/Al_2O_3 as catalyst enhanced this amount to 87%, and the amount of the outlet ozone was decreased from 58 ppm to 14 ppm due to decomposition of ozone on the surface of the catalyst [25]. In another study, removal of a mixture of benzene, toluene and p-xylene with the concentration of 1.5, 1.4 and 1.2 ppm, respectively in the presence of 46.7 ppm of ozone and MnO_x/Al_2O_3 as the catalyst showed a conversion of 94%, 97% and 95%, as well as reducing the outlet ozone concentration to 1.9 ppm [26]. It should be noted that even the catalyst cannot totally remove the generated ozone and the ozone level in the outlet is still much higher than 20 ppb specified by the Health Canada's Residential Indoor Air Quality Guideline [27], for a long-term exposure.

The reaction kinetic of ozone formation can be optimized by controlling the operating parameters including the power density, pressure, air–gap width between the electrodes, electrodes' configuration and the properties of the dielectric barrier in a plasma system [14]. Up to now, various types of the reactors with different sizes, as well as electrode configurations and types have been utilized and the removal efficiency of VOCs is investigated in these reactors [3,28–32]. However, despite the importance of controlling the ozone level for indoor applications, the impact of design parameters on the ozone generation along with energy consumption in a DBD system has not been specifically investigated. Accordingly, this paper reports the outcomes of a series of experimental studies, which investigated the impact of residence time, type and configuration of the ground electrode, and reactor size on the energy density and the rate of ozone generation of a DBD micro-reactor.

2. Experimental setup and apparatus

Fig. 1 illustrates the schematic diagram of the set-up.

Fig. 1 shows that compressed air (A) passes through a pressure regulator (B) to adjust the pressure to 10 psig. The airflow rate is set and controlled by a mass flow controller (MFC) (C) and passes through a DBD reactor (D). The applied voltage is provided by a high voltage generator array (E) which is explained later. The airflow rate is set at 0.6 L/min and the experiment is performed at ambient temperature (21 ± 1 °C). The concentration of generated ozone in the reactor is measured downstream of the reactor using a Model 202 Ozone Monitor (F) (2B Technologies, An InDevR Company), which is capable measuring ozone concentration in a linear dynamic range of 1.5–250 ppm with resolution of 0.1 ppb. The measurement principle is based on the absorption of UV light at 254 nm. The measurement interval is set to 10 s. For each test, at least 20 reading of the ozone concentration is recorded and the average amount is used as the ozone concentration.

In this study, two sizes of the quartz tubes were employed as reactor. Specification of these reactors is summarized in Table 1. The concentric geometry of reactors consists of a centered stainless steel-316 rod (D: 5 mm, L: 150 mm) as an inner electrode.

The ground electrode consists of three metals in four different configurations, including stainless steel with two mesh sizes of 600 μm (SS-T) and 90 μm (SS-F), aluminum foil (Al), and silver paste (Ag). To prepare silver as the ground electrode, the outer surface of quartz tube is covered with a thick layer of silver paste (Aldrich, ρ = 5–6 μΩ). The reactor is then cured at 180 °C for three hours. The electrodes configurations are shown in Fig. 2.

The schematic of the high voltage power supply, indicated by HV in Fig. 1, is illustrated in Fig. 3.

The function generator (B) (BK PRECISION, Model 4011A), shown in the left panel of Fig. 3, uses AC power (A) as input and generates sinusoidal waveform with the adjustable frequency between 50 Hz and 2 kHz. The output of function generator is applied to a wideband AC power amplifier (C) (Model AL-600-HF-A, Amp-Line Corp.), which transforms the input signal of 0–2 V_{rms} to an adjustable voltage in the range of 0–28 Vrms and frequency between 20 Hz and 800 kHz, with an output power of maximum 600 W. Afterward, a high voltage transformer box (D) (Model AL-T250-V25/10K-F50/2K, Amp-Line Corp.), transforms the primary voltage to a secondary voltage up to 30 kV_{p-p}. The output power and the bandwidth of the transformer are 250 W, and 50 Hz to 2 kHz, respectively. The block diagram of the high voltage transformer and the added resistors (I, J, and K), are illustrated in the right panel of Fig. 3. The coil (H) intensifies the input voltage by 440 times. The high voltage output is loaded by the DBD reactor (F) via resistor I, while the outputs of resistors J and K are sent to a digital oscilloscope (E) (Tektronix, TBS1052B-EDU, 50MHZ, 2CHANNEL) to monitor the voltage and current signals of the system over time. To make sure about the voltage which is delivered to the reactor, the high voltage in the load part is also measured by a 30 kV high voltage probe (G) (Keysight N2771B). All parts of the set-up are connected using high voltage wires.

The measured data are used to evaluate the energy consumption of the system. For a plasma system the applied energy density into the reactor, known as specific input energy (SIE, JL^{-1}), is an indicator of the energy consumption, which is defined as: