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Electromagnetic and Ozone Emissions from Dielectric Barrier Discharge Plasma Actuators

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I. Introduction

A. Motivation

Dielectric barrier discharge plasma actuators, herein referred to as plasma actuators, are versatile flow control tools that have the potential to serve a wide variety of applications. These lightweight devices have fast frequency response, a low profile, and can be laminated to curved aerodynamic surfaces. Plasma actuators have demonstrated practical ability in separation control [1,2], aircraft noise reduction [3], reducing losses associated with flow over compressor blades [4], wake control [3], and boundary-layer control [5]. However, one of the major drawbacks with the use of plasma actuators is the high voltage required for their operation. This is a concern for the implementation of these devices in industry, specifically with respect to power supply logistics and risks to human health. The first substantial health risk is the significant amount of ozone and nitrous oxides generated during the operation of plasma actuators [6]. In fact, the ozone generation properties of plasma actuators are commonly used for decontamination purposes [6] and have even been used recently as a diagnostic tool [7]. However, ozone is known to be a powerful oxidant and potent respiratory hazard in humans and animals. The other major health risk worth mentioning is the potential exposure to electromagnetic radiation.

Despite extensive in-laboratory usage, studies within the community have often neglected to evaluate the severity and extent of electromagnetic or ozone emission caused by plasma actuator operation. The purpose of this study is to determine the distances from an operating plasma actuator at which the electromagnetic field (EMF) strengths meet or exceed the standards for maximum exposure to prevent adverse health effects as well as to evaluate the rate of ozone generated during operation of these devices. This study serves as a guide for those who come into contact with plasma actuators and should illustrate when countermeasures to mitigate exposure to electromagnetic radiation and/or ozone are advisable or necessary.

B. Health and Safety Considerations

Plasma actuators typically operate on the lower end (typically less than 20 kHz) of the radio-frequency (RF) range on the electromagnetic spectrum. The RF range supports many widely used applications including, but not limited to, radar, satellite, navigation, wireless, cellular, and telecommunication devices [8]. Studies on the potential health effects associated with RF radiation have examined concerns such as deoxyribonucleic acid (DNA) damage, tumor promotion, human cancers, behavior and cognitive functions, gene and protein expression, immune response, and reproductive functions [9]. Exposure to RF fields is known to induce internal body currents and energy absorption in tissues [3]. Adverse health effects from exposure to RF sources is predominantly related to excitatory tissue stimulation from acute exposures for frequencies from 3 kHz to 100 kHz and the occurrence of tissue heating for frequencies from 100 kHz to 3 GHz [9]. The Institute of Electrical and Electronics Engineers’s (IEEE’s) standard C95.1-1999 [10] and Health Canada’s Safety Code 6 [9] both provide outlines for the limits of human exposure to electromagnetic energy in the radio frequency, based on ongoing review of published scientific studies. According to Health Canada, there exists no scientific evidence of chronic or cumulative health risks from RF energy at levels below specified limits provided by Safety Code 6. Both the codes provide exposure limits for controlled and uncontrolled environments. Situations that fail to meet the codes’ awareness criteria are considered uncontrolled environments in which RF energy has been insufficiently assessed and/or where persons within the environment have not received adequate RF awareness training and lack the means to assess or mitigate their exposure to RF energy. The maximum allowable electric and magnetic field strengths provided for both controlled and uncontrolled environments are listed in Table 1. These limits can be used to evaluate the RF field surrounding an operating plasma actuator to establish a safe working distance.

Similarly, the Residential Indoor Air Quality Guideline-Ozone issued by Health Canada [11] and the U.S. Department of Labor’s workplace limits [12] will be used to compare the maximum exposure levels of ozone with those found in the environment surrounding an operating dielectric barrier discharge (DBD) plasma actuator. Ozone can be formed through the ionization and breakdown of oxygen molecules in air. Thus, the operation of plasma actuators continuously forms significant amounts of ozone, which is a strong oxidizing agent that reacts rapidly with exposed surfaces and other constituents in air. Ozone is a colorless gas and, as such, may go undetected in lower concentrations in indoor environments. The science assessment document for ground-level ozone issued by Environment Canada and Health Canada [13] concluded that there was a significant association between ambient ozone levels and adverse human health effects (mortality and morbidity), as well as reduced vegetation growth and crop yield. In 2003, under the Canadian Environmental Protection Act, ozone was declared toxic [11]. In humans, acute exposure to ozone of up to 4 h in healthy adults was shown to decrease forced vital capacity, forced expiratory volume in 1 s, forced inspiratory volume, and tidal volume. Acute
ozone exposure was also shown to increase breathing frequency and cause pain upon deep inhalation. These effects can be seen at an ozone level of 80 ppb [11], which is the lowest observed adverse effect level for this exposure duration in accordance with Health Canada. Prolonged exposure for 4 to 8 h caused decreased lung functions and increased pain upon inhalation. The Residential Indoor Air Quality Guideline–Ozone issued by Health Canada (2010) recommends a residential maximum exposure limit of 40 μg/m³ (20 ppb) ozone, based on an averaging time of 8 h [11]. This exposure limit would still be half of the no observed adverse effect level for this exposure duration.

Although ozone production by plasma actuators is common knowledge in the field, studies have yet to focus on the ozone levels produced by plasma actuation and how they compare with safety standards for ozone exposure. In a subsequent study, the Residential Indoor Air Quality Guideline–Ozone levels set forth by Health Canada in 2010 [11] and the U.S. Occupational Safety and Health Administration (OSHA) guidelines [12] will be used to compare the recommended maximum exposure levels of ozone with those found in the environment surrounding an operating plasma actuator. These guideline exposure limits are summarized in Table 2, where the short-term exposure limit (STEL) and permissible exposure limit (PEL) are listed. These guidelines illustrate if action is required to reduce human exposure to ozone during plasma actuator research and the intensity of countermeasures to be taken.

### II. Experimental Setup

#### A. Plasma Actuators

Typical DBD plasma actuators consist of two asymmetrically arranged electrodes separated by a dielectric material. One electrode is left exposed to the environment, whereas the other is grounded and encapsulated in some insulating material. This configuration, when supplied with sufficient voltage potential, generates an electric field, weakly ionizing the ambient gas above the encapsulated electrode and forming a plasma discharge. The charged plasma in the presence of an electric field results in a wall jet that expels fluid away from the exposed electrode toward the grounded electrode as shown in Fig. 1. Two separate electromagnetic (EM) radiation investigations were conducted in the present work using actuator 1 and actuator 2. Ozone exposure experiments were conducted using actuator 3. Dimensions of the actuators used in this study are summarized in Table 3. The actuators consisted of two asymmetrically arranged 0.07-mm-thick (adhesive included) copper tape electrodes separated by a polymethyl methacrylate dielectric substrate with no horizontal gap or overlap between electrodes. The grounded electrode was encapsulated with a 0.27-mm-thick Kapton® tape.

### B. Electromagnetic Measurements

Electromagnetic field experiments were conducted in an open area away from additional EMF sources. The plasma actuators used in the EMF experiments were powered using a Trek® model 20/20C high-voltage amplifier. A sine waveform was provided to the amplifier using an Agilent® 33220A function generator. A schematic of the plasma actuator circuit is shown in Fig. 2.

Both electric field and magnetic field strengths were determined using a handheld Gigahertz Solution® ME 3851A field reader, which has a measurement accuracy of ±2% and a frequency range of 5 Hz to 100 kHz. Measurements were carried out in accordance with Health Canada guidelines for the measurement of radio frequency fields at frequencies from 3 kHz to 300 GHz [9]. Two separate EMF investigations were conducted. In the first set of experiments: actuator 1 was operated at 16 kilovolts peak to peak (kVpp) and 3 kHz. The electric and magnetic field strengths were measured at these operating condition along a single axis (radially) for several angles about the actuator. In the second set of experiments, the electric and magnetic fields surrounding actuator 2 were characterized for a variety of operating voltages (up to 12 kVpp) and frequencies (up to 11 kHz). The field strengths were calculated from the three-axis measurement data taken.

For the first tests with actuator 1, a spatial grid was constructed at various heights adjacent to the actuator while ensuring the parallelism to the y–z plane of the actuator. The actuator was rotated with respect to the grid such that the location of the electric and magnetic field...
limits could be determined and recorded. Locations of field limits were found for select rotations of 0, 45, 90, 270, and 315 deg from the $z$-axis of the actuator, as shown in Fig. 3. The field limits for the unmeasured angles were taken to be the same as the measured limits reflected from the $x$–$y$ plane. The maximum field locations at these rotations were found at heights above the actuator of 0, 50, 100, and 150 cm. Distances were measured from the center of the actuator with an estimated uncertainty of $\pm 0.0005$ cm. All angles and heights were measured from the center of the actuator at the plasma-forming interface between the exposed electrode and the dielectric surface. The background electromagnetic reading was taken before actuation to ensure minimal influence on measurements. For the EMF measurements with actuator 1, readings were taken with the ME 3951A field meter pointed towards the actuator $x$-axis, parallel to the orientations shown in Fig. 3 at various heights.

For the EMF characterization experiments, the three-axis resultant electric and magnetic field strengths were recorded for various orientations about actuator 2. The actuator surface was oriented normal to a mock-floor platform surface, as shown in Fig. 4, and able to pivot about its center. Specific distances from the actuators center were indicated along the length of the platform. A height ladder was constructed such that measurements could be made at specific heights from the actuator center with the handheld measurement device. Using the height ladder at the distances indicated on the platform, the field measurements were obtained for a spatial grid of points. The actuator was pivoted about its center such that this spatial grid of field measurements was obtained at various orientations relative to the actuator as defined in Fig. 3.

For increased repeatability in electric field measurements, the field meter was grounded and held in front of a square grounded copper shield with dimensions of 50 cm, as per the ME 3951A operators manual. The field meter indicated the rms value of the field along the axis parallel to the device for electric fields and perpendicular to the display screen for magnetic fields. Each field of interest was measured along three axes, as indicated in Fig. 4. The resultant of the three-axis measurements was recorded for each height, distance, and orientation in order to quantify the magnitude of the field strength at each of these locations surrounding an operating plasma actuator. In Fig. 4, $V$ is the voltage applied to the high-voltage electrode, whereas $V_p$ is the voltage measured across a probe capacitor $C_p$ applied between the ground electrode and the ground in order to measure power consumption from the actuator [14].

C. Ozone Measurements

For ozone generation measurements, the DBD plasma actuator was placed in the center of a closed cylindrical chamber, which was 80 cm in diameter and 80 cm in length. A small fan inside the chamber was used to improve homogeneity of the ozone concentration within the chamber. The ozone concentration was measured every 10 s for approximately 5 min. The slope of the increasing concentration was used to measure the quantity of ozone being produces in parts per billion per second, which can be converted to grams per second with the known volume of the chamber. The usable internal volume, discounting internal equipment and structure, was 0.36 m$^3$. The experimental setup used for ozone measurements is pictured in Fig. 5.

A function generator [PXI-5402 (14 bit, 20 MHz, 10 V)] from National Instruments and a LabView™ program were used to generate the zero offset sinusoidal signal applied to the actuator. The signal was then amplified (times 2000) with a Matsusada® AMP-20b20. A range of voltages between 2 and 20 kVpp and frequencies between 1 and 20 kHz were investigated. Data-acquisition equipment and a LabView interface were also used to measure and record the current crossing the electrodes of the actuator. This equipment consisted of a PXI-6052E from National Instruments and a current probe from Pearson®, model 2100. The ozone concentration was measured with an ozone meter, model 106-L from 2BTechnologies™, with a National Institute of Standards and Technology traceable accuracy of 2%. To ensure operator safety, the electric and magnetic fields were measured with the low-frequency field strength meter from a Gigahertz Solution model ME-3951A with a 2% accuracy, as described previously. The maximum electric and magnetic field was measured before taking ozone readings and found to be 80 V/m and 30 nT, respectively, at a 20 cm distance around the closed chamber.
III. Results

A. Electromagnetic Measurements

The exposure limit locations were found for actuator 1 following the procedure outlined in Sec. II.B. The background electric field was measured before plasma actuation to be 1 V/m at distances 60 cm away from the actuator. The background electric field was unchanged with the Trek amplifier, and other instruments turned off or on (but without plasma formation). Three-dimensional representations of the exposure limit locations can be found in Fig. 6. An illustration of the locations of maximum electromagnetic exposure limits for both IEEE controlled and Health Canada Safety Code 6 controlled environments can be seen in Fig. 6. Field lines based on interpolated data are also shown to illustrate how the electric field emanates from the actuator. An elliptical fit was approximated using the measured and reflected data based on the assumption of electric field’s symmetry about the x–y plane. The magnetic field was also measured to investigate if there were any safety concerns. At the operating conditions of 16 kVpp and 3 kHz, the magnetic field measured at a height of 50 cm for all degrees was approximately equal to 0.02 A/m, which was significantly lower than the recommended maximum for an uncontrolled environment of 90 A/m. This demonstrated that the generated magnetic field was not of concern for any of our test cases.

B. Characterization of Electromagnetic Fields

The electric and magnetic fields for actuators 1 and 2 were characterized for various operating conditions according to the procedure detailed in Sec. II.B. The uncertainty in resultant electric and magnetic field strengths were calculated in quadrature according to standard error analysis procedures using an individual component error of ±2%, as per the field meter specifications for both sensors. Uncertainty in the radial distance to the actuator center was estimated at ±4%. All surrounding equipment other than the meter was switched off. The background electric and magnetic field strengths in the experimental area were then measured with the Trek and all other electronics turned off. The background field was found to be smaller than the resolution of the EMF analyzer, i.e., 0.1 V/m and 0.1 nT, respectively. From the plots in Fig. 7a, two major conclusions can be drawn. First, the electric field strength $E$ is a function of the radial distance $r$ from the actuator center, regardless of position about the actuator. Second, the increase in operating voltage increases the strength of the resultant electric field. These results are more explicitly expressed in Fig. 7b. For various operating voltages, the trend $|E| \propto 1/r^2$ was found consistently over all orientations tested. This is the same result one would expect with an electric field generated by a series of point charges similar to that modeled by Yoshida et al. [15]. Because the electric field strength is dependent on the radial distance from the actuator, the effect of various operating voltages was compared at specific grid coordinates, the radial distances of which are displayed in Fig. 7a. The linear relation $E \propto V_{pp}$ was found, consistently, for all orientations tested. The effect of operating frequency on resultant field strength was also investigated and found to be insensitive.

It was found that the magnetic field induced by the plasma actuator was quite weak, dropping to essentially zero by a radial distance of approximately 1.5 m. Figures 7c and 7d show the magnetic field strength as a function of both radial distance from the actuator and operating voltage, respectively. The trends $|B| \propto 1/r^2$ and $|B| \propto V_{pp}$ were found via weighted least-squares regression consistently over all orientations tested. These relations mimicked those of the electric field strength, given the proportional relationship between electric and magnetic fields.

It should be noted that operating the plasma actuator at 4 kVpp failed to produce visible plasma discharge. This falls under the operating regime of “dark discharge,” where part ionization of the gas and electron avalanche occurs for operating voltages below the breakdown voltage of the gas. A review of Figs. 7a–7d shows that operation of the plasma actuator in the dark discharge regime does not differ from operation in the glow discharge regime with respect to electric and magnetic fields.
magnetic field behavior. This emphasizes the importance of EMF awareness for researchers working with or in close proximity to plasma actuators, as even operation below breakdown field strength can generate measurable electromagnetic radiation. For actuator 2, maintaining a distance of 1.5 m guaranteed EMF radiation exposure below the limits set forth by Health Canada for a controlled environment (170 V/m) and the range of voltages considered here (4–12 kV). Although the workspace is considered a safe distance from the operating actuator according to Health Canada, the ME 3951A user manual\(^{11}\) recommends exposure limits of 1 V/m (electric field) and 20 nT (magnetic field) for frequencies above 2 kHz in areas where people spend substantial amounts of time, such as the workplace. As such, for the EMF experiments presented in the current work, prolonged exposure to any operating plasma actuators was minimized and sufficient distance was maintained while operating actuators.

C. Ozone Measurements

Ozone generation rate was quantified for a closed chamber with a 5 min actuator operation time. The *Residential Indoor Air Quality Guideline—Ozone* issued by Health Canada (2010) recommends a residential maximum exposure limit of 40 g/m\(^3\) (20 ppb) ozone based on an averaging time of 8 h \([11]\). The plasma actuator generated up to 350 ppb/s during the experiments, which would rapidly exceed the amount recommended by the Health Canada guideline in a small room. In this case, a closed chamber with proper ventilation was mandatory for DBD plasma operation. The ozone production as a function of applied voltage (peak-to-peak) is shown for various frequencies in Fig. 8a. The ozone production was found proportional to \(V_{pp}^{3.5}, V_{pp}^{2.9}\), and \(V_{pp}^{2.0}\) for operation at 1, 2, and 3 kHz, respectively. Ozone generation is also shown as a function of operating frequency for several applied voltages in Fig. 8b. It is shown that ozone generation scales with operating frequency in a nearly linear fashion. The power law behavior of ozone production with voltage is reminiscent of the relation between power consumption and applied voltage typically.

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reported in the literature [14,16]. Similarly, the relation between power consumption and operating frequency is often described or approximated as linear in plasma actuator studies [14,16]. The results shown in Figs. 8a and 8b indicate that the ozone production is proportional to the power consumed by an operating actuator. The linear behavior of ozone generation with frequency is demonstrated in Fig. 9 for frequencies up to 10 kHz. The data presented here can be used to estimate the ozone production as part of a diligent experiment design. This can help an experimentalist avoid situations where ozone production could pose a significant health risk.

IV. Conclusions

Characterization of electromagnetic fields and measurement of ozone generation around a typical laboratory plasma actuator were performed. It was found that, although magnetic field exposure was not a major health concern, both the electrical field and ozone production were potential health hazards. The magnetic field was found to be much lower than the published standards and would typically not warrant any extra precaution. On the other hand, the results demonstrated that the electric field strength of an actuator operating within a typical range of voltages and frequencies could exceed recommended safety standards. The electric and magnetic field strengths were found to increase linearly with applied voltage ($E \propto V_{pp}$ and $B \propto V_{pp}$) but independent of operating frequency for the range of frequencies tested. Electromagnetic field strengths were also found to be related to the radial distance from the actuator center, similar to the fields surrounding a point charge: $|E| \propto 1/r^2$ and $|B| \propto 1/r^2$. Evaluation of EMF exposure is an important consideration in experimental setup design for the health and safety of both humans and equipment. Electromagnetic interference, also known as radio-frequency interference for the radio-frequency spectrum, is a disturbance affecting electrical circuits caused by external EM radiation, which may result in degradation or loss of data. One of the most effective methods to reduce electromagnetic interference effects is enclosing the high-voltage source within a grounded metallic mesh, or Faraday cage. The electrical charges within a Faraday cage’s conducting material distribute to cancel the external EM radiation, which may result in degradation or loss of data. Ideally, plasma actuator experiments should be contained within Faraday cages such that electromagnetic radiation is not a health concern for researchers working with or within the same space as operating devices. The use of Faraday cages should also be used to mitigate electromagnetic interference effects on laboratory equipment.

The other major health concern with plasma actuators is the production of ozone. It was found that, in a small room, plasma actuator operation could quickly exceed the recommended exposure limits listed in Table 2. In this case, an isolated chamber with external venting would be required for safe operation. A power law relation between ozone generation and applied voltage at constant frequency ($\propto V_{pp}^{2.9-3.5}$) and a linear relation between ozone generation and operating frequency were found. In summary, it was found that plasma actuators presented a source of potential health risk due to both electric field radiation and ozone production. These health and safety risks were nonnegligible and should be assessed and addressed before experimentation with these devices for the protection of researchers and research equipment.

It is important to emphasize that the aforementioned conclusions only consider ac-driven plasma actuators operated at frequencies of the order of kilohertz. Other types of plasma actuators, such as nanosecond-pulse driven actuators, may behave differently, and thus should be considered in future studies.

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References


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