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MORTALITY OF INSECTS ON THE SURFACE OF PLANTS USING AN ATMOSPHERIC PRESSURE PLASMA DISCHARGE

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Abstract

This paper presents evidence for the efficacy of atmospheric pressure plasma discharge (APPD) in the absence of chemical species and above ambient gas temperature on insect control. The treatment of a model insect system, green peach aphids, was carried out on a plastic surface and tobacco leaves. Both treatments show a reduction in green peach aphid populations, but their mortality on a plastic surface (88% mortality) was significantly higher than that on tobacco leaves (40%) for a 120 s treatment. The reduction in mortality of green peach aphids on leaves is likely from the leaf acting as a lightning rod that is drawing the plasma away from the aphids. For practical applications, the thermal component of the discharge will accompany the plasma treatment to decrease treatment duration.

Introduction

Traditional methods of insect control are effective, but concerns about genetic modification of plants and the long-term impact of chemical pesticides are common in the general public. This has led to studies examining possible alternative pest control methods. Atmospheric pressure plasma discharge (APPD) treatment of insects has been explored as a method of pest control (Roe *et al.*, 2003). Atmospheric pressure plasma discharges are mostly neutral gases with a small fraction ($<10^{-6}\%$) of electrically charged particles (electrons and ions). The APPD is commonly produced using parallel metallic electrodes covered in a thin layer of plastic or ceramic with audio frequency high voltage applied to the electrodes. In some cases, the atmosphere is modified with helium or argon to reduce the magnitude of the high voltage signal required to generate the APPD.

The research to date has shown efficacy of the APPD treatment for insect control when the ambient gas temperature is elevated. However, to understand the role of the plasma alone, the thermal component of the discharge was eliminated. The atmospheric pressure plasma discharge has a number of properties that may damage an insect other than thermal damage. The chemical species produced as a bi-product of the discharge, the high voltage required to generate and sustain the discharge, the helium atmosphere used to reduce the power to generate the discharge, and the charged particles are all potentially damaging to an insect. *Myzus persicae* (Boddie), green peach aphids, were selected as a model system for the study since previous results (Roe *et al.*, 2003) showed short exposure to the APPD resulted in high mortality. In this paper, we present results that clearly show that non-thermal, non-chemical APPD is capable of inducing mortality on the model system.

Materials and Methods

Plasma Device

The devices that generate non-thermal atmospheric plasma come in a variety of sizes, electrode configurations and operating frequencies (Kanazawa *et al.*, 1988; Herrmann *et al.*, 1999; Kelly-Wintenberg *et al.*, 2000; Laroussi *et al.*, 2000; Montie *et al.*, 2000; Roth *et al.*, 2000; Moisan *et al.*, 2001). For the experimental setup in this paper, a parallel plate configuration was chosen with a 5.0 cm electrode separation and an applied potential of ~ 4 kV_{RMS} at 4 kHz (Figure 1). The instrument is housed in an acrylic enclosure in order to contain the carrier gas, helium. Helium gas is injected between the electrodes at a constant flow rate of 34 standard liters per minute (slpm) for 60 min to relax the requirements to produce the desired discharge and reduce the ambient gas temperature. In order to reduce the temperature in the discharge even further, the electrodes are actively cooled by distilled water circulated at 7 °C. The specifications for the instrument and the actual conditions used for the generation of atmospheric plasma are provided in Table 1.

The copper electrodes (16 by 20 cm) are pressed against Garolite G-7 (0.793 mm). The Garolite G-7 acts to isolate the electrodes from the discharge and create a dielectric barrier discharge. The Garolite G-7 allows the discharge to remain diffuse over a wide range of operating conditions. When the frequency is too low (<1 kHz) or the applied potential is too high, the diffuse discharge will collapse into a thermal arc. The arc is thermal plasma (>200°C) that travels freely between the electrodes. When a thermal arc forms, the dielectric material is severely damaged along with the treated commodity. Every effort is made to prevent the formation of the thermal arc. Throughout the course of the experiments, the thermal arc was never observed.

In order to ensure the discharge was non-thermal, K-type contact thermocouple measurements of the discharge were taken with an electrically insulated thermocouple. The thermocouple was placed in the discharge starting at the lower electrode and moved upward in 1 cm increments until 4 cm above the lower electrode. The measurements were performed without insects present but under identical operating conditions to the insect treatments. The key difference between the recent and previous measurements (Roe *et al.*, 2003) is that K-type contact thermocouples were used instead of infrared thermocouples. Infrared thermocouples are calibrated for use with solid surfaces. The lower density gas shows a reduced temperature from the true measurement. The insulated K-type contact thermocouple resides in the discharge and measures the temperature increase of the gas directly.

A second diagnostic tool used to examine the APPD was optical emission spectroscopy. The APPD emits light that is characteristic of atoms and molecules in the discharge. By knowing the characteristic wavelengths of the emitted light, an assessment of the chemical species in the discharge is possible for species that radiate in the range of the optical spectrometer.

Tests with the Green Peach Aphid

Green peach aphids were obtained from the Department of Entomology at North Carolina State University. These aphids are routinely maintained on tobacco in the green house.

Insect Thermal Treatment. For this assay, 25 insects were placed in a plastic container (3 cm high) with a BugBed 123 (Green Thumb Group, Downers Grove, IL) mesh top (11.5 cm diameter) and bottom (10.0 cm diameter). The insects were exposed to the atmosphere of an oven for 120 s at 25, 40, 45, and 50 °C. Each treatment was replicated four times.

Insect Plasma Treatment. For this assay, 25 insects were placed in each plastic container (as described earlier) or on a tobacco leaf in each plastic container and then moved into the plasma field. The controls were either held inside the acrylic enclosure (exposed to He) but not placed into the plasma field, or held outside (no He or plasma exposure). Each treatment and control was replicated three times.

After the plasma or thermal treatment under the conditions described earlier, the insects were incubated at 27°C, 100% relative humidity and no light. The plasma exposure times are given in the Results and Discussion. Mortality was assessed at 1, 3, 5 and 24 h for the plasma treatment. Mortality was assessed at 1, 3, and 24 h for the thermal treatment. Mortality in these experiments was defined as lack of movement when the aphids were touched with a camelhair brush.

Results and Discussion

As stated above, the APPD has a number of potential properties that may damage an insect. The chemical species and the ambient gas temperature are two key parameters that may be controlled in the discharge. Increasing the helium volume fraction to nearly 100% controls the chemicals species. When helium dominants the chemical make up of the discharge, chemical reactions tend to be suppressed by reducing the volume fraction of chemical species. The calibrated optical emission spectrum (Figure 2) clearly shows that helium is the dominant chemical species in the plasma with some quantity of molecular nitrogen.

The second key concern is the ambient gas temperature of the discharge. By passing electrical current through a gas, the temperature of the gas will increase by dissipating the energy required to carry the current. In order to limit the gas temperature in the APPD below 40 °C, the electrodes were actively cooled in our studies. Unfortunately, actively cooling the electrodes was insufficient in limiting the ambient gas temperature in the APPD. A current of 30 mA_{RMS} (Root Mean Square current) or less was required to limit the ambient gas temperature in the APPD below 40 °C. Figure 3 shows the temperature of the discharge between the electrodes when the electrodes were and were not cooled with distilled water. The ambient gas temperature was approximately 37 °C between the electrodes when the electrodes were actively cooled.

To evaluate the role of temperature alone on green peach aphid mortality, a set of thermal tests were conducted. Figure 4 shows the green peach aphid mortality after being treated at different temperatures for 120 s. The mortality of the aphids was quite low below 50 °C. It was apparent from these studies that thermal effects alone in 37 °C APPD should not elicit high aphid mortality.

When green peach aphids were treated with 37 °C APPD, mortality increased with treatment durations from 0 to 120 sec (Figure 5). This mortality must be the result of plasma and not thermal effects, since mortality was low below 50 °C (in the absence of plasma, Figure 4). Also note that mortality for the thermal treatments was the same at 1, 3 and 24 h at each test temperature (Figure 4) while mortality increased with time post-treatment with 37 °C APPD. This argues for a different mechanism for the effect of thermal versus 37 °C APPD on mortality. The mechanism of action of plasma on insect mortality is unknown. The correlation between treatment duration and mortality at 1 and 24 h post treatment is shown in Figure 6.

The data for the 1 and 24 h time after treatment both show a linear correlation with a $R^2 = 0.976$ for the 1 h time after treatment and a $R^2 = 0.945$ for the 24 h time after treatment.

The final point of interest for the APPD treatment is the reaction of the green peach aphids on leaves. In a practical application, aphids will inhabit a leaf instead of a plastic container. Previous work by Roe *et al.* (2003) has shown that a leaf can significantly reduce the mortality of green peach aphids when treated with APPD. The result with the non-thermal, non-chemical APPD is the same (Figure 7). The reduction in aphid mortality on tobacco leaves compared to aphids on plastic is likely due to a change in the level of plasma exposure. During the aphid treatment on tobacco leaves, the APPD is more intense around the edges of the leaves than in the center. Since the average power was the same for the aphid treatment on plastic and the aphid treatment on tobacco leaves, the exposure level was reduced for the aphids on the tobacco leaves. In effect, the edges of the leaf were drawing the APPD treatment away from the aphids. The same principle is used in lightning rods that are used to draw lightning away from a building.

In summary, the non-thermal, non-chemical APPD treatment of green peach aphids produced high mortality after a 120 s treatment on a plastic surface. These results show that plasma alone (without thermal effects) is lethal to aphids. A similar treatment with the green peach aphids on tobacco leaves in the same containers produce lower mortality, presumably because the leaves are acting as lightning rods that draw the plasma away from the aphids on the leaf surface. Most likely, an APPD with elevated ambient gas temperature will be needed to reduce treatment time and plant damage and to produce the level of mortality needed for this technology to be used as an effective insect control method.

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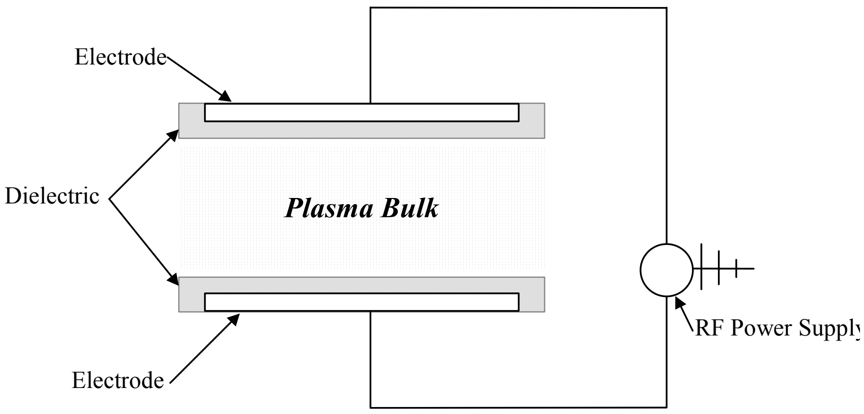

Figure 1. Diagram of APPD device.

Table 1. Operational parameters for the APPD device.

Parameter	Value	Experimental Value
Peak Voltage	15 kV	6 kV
Peak Current	120 mA	53 mA (30mA$_{RMS}$)
Peak Power	500W	100W
Frequency Range	2-15 kHz	4 kHz
Electrode Area	320 cm^2 (16 cm by 20 cm)	320 cm^2 (16 cm by 20 cm)
Electrode Gap	1.5-13.0 cm	5.0 cm
Carrier Gases	He, Ar	He
Other Gases	Air, N_2, H_2, O_2	Air
Barrier Material	Plexiglas (5 mm), Garolite G-7 (0.79 mm)	Garolite G-7 (0.79 mm)
Electrode Material	Cu	Cu

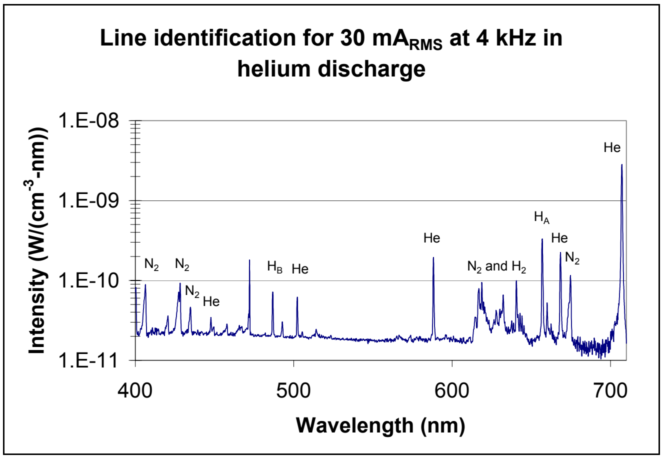

Figure 2. Optical emission spectrum for PALADIN DBD with 60 min of helium fill at 30 mA$_{RMS}$, 4 kHz in a 5 cm gap.

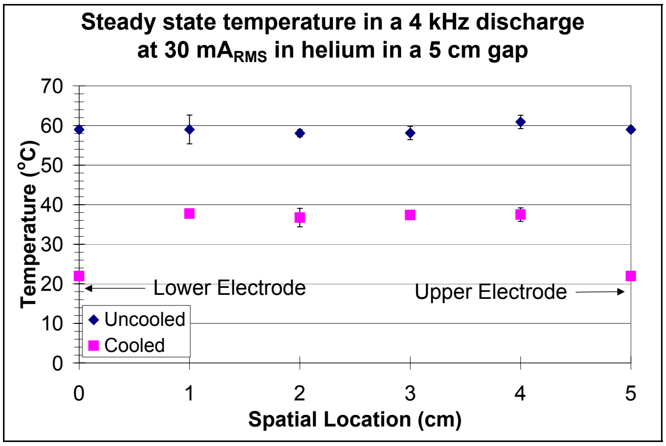

Figure 3. Comparison of gap temperature with and without active cooling at 4 kHz in a 5 cm gap at 30 mA$_{RMS}$. Mean +/- S.D. (n=3).

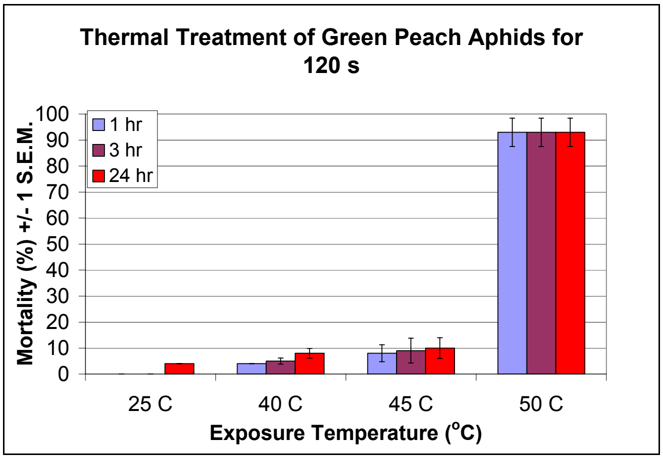

Figure 4. Thermal treatment of green peach aphids for 120 s.

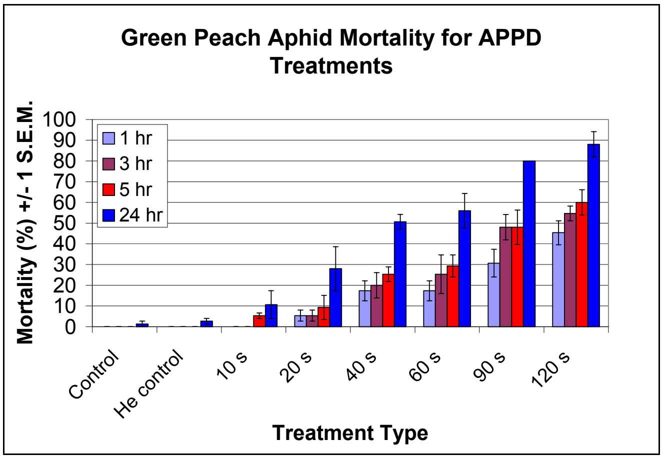

Figure 5. APPD treatment at 4 kHz, 30 mA$_{RMS}$ in helium of green peach aphids. The control was held outside of the acrylic enclosure. The He control was held inside but not placed into the plasma field.

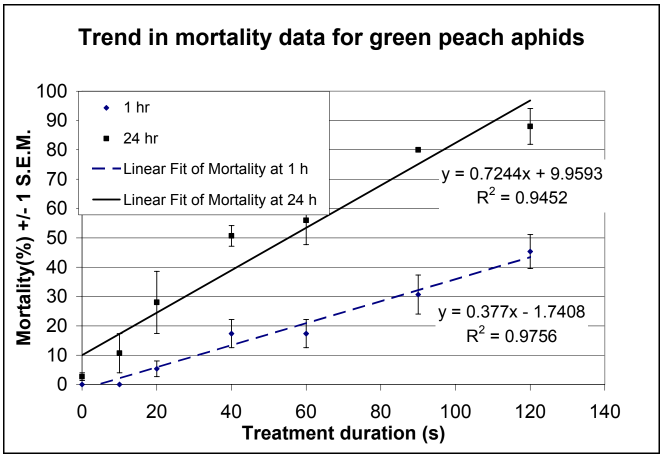

Figure 6. Mortality trend for plasma treated green peach aphids.

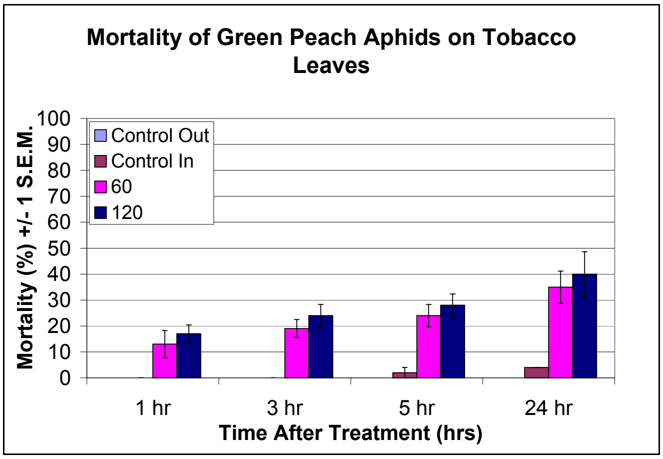

Figure 7. Treatment of green peach aphids on tobacco leaves with APPD. No mortality was noted for aphids held outside of the acrylic enclosure and for those held on the inside but not placed into the plasma field.