Low Voltage Ionic Wind Generation using Piezoelectric Transformers

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***Abstract*—Ionic winds are air flows that are generated when ions driven by an electric field collide with air molecules. This collision transfers momentum from the ion to the air molecule, thus generating a bulk flow. Typically, ionic winds are generated by gas discharges requiring large input voltages (>5 kV) applied between two electrodes. The need for such large voltages limit the practicality of ionic wind devices for mobile and handheld technologies. As an alternative, piezoelectric transformers use electromechanical coupling to produce large gains in voltage with only low input voltages. These transformers provide the largest gain in voltage when the driving frequency matches the resonance frequency of the crystal. In this work, a piezoelectric transformer is used as an electrode in an ionic wind device. Using a piezoelectric transformer reduces the required voltage needed to generate an ionic wind by two orders of magnitude when compared to a standard device that uses only metal electrodes. Two different ionic wind configurations were examined along with two different types of piezoelectric materials. It was shown that the resonance frequency of the piezoelectric transformer was a function of its surroundings, and a simple circuit model was developed to better understand how changes to its operating conditions could alter the performance of the piezoelectric-driven ionic wind.**

I. Introduction

Due to their unique electromechanical coupling, piezoelectric materials are frequently used for a wide variety of applications. When put under an applied mechanical stress, the piezoelectric becomes polarized and produces an electric field. This process is reversible such that when an electric field is applied to a piezoelectric, it mechanically deforms. This coupling can be attributed to the non-centrosymmetric positioning of atoms within the material's unit cell, which causes an uncompensated movement of charge in a single direction when a mechanical stress is applied [1]. This unique property allows for piezoelectrics to be ideal for use as sensors or actuators. Analogous to magnetic transformers, which convert between electrical and magnetic energy to produce a gain in applied voltage, piezoelectric transformers convert between electrical and mechanical energy to produce a similar effect [2]. Since their invention, piezoelectric transformers have been used in a number of different applications including as a transformer to power CCFL backlighting in portable electronics [3] or as a DC/DC converter [4]. Recent research has shown that piezoelectric transformers can generate voltage gains on the order of 10,000 under the proper electrical load [5], which makes them a promising candidate for a number of different high voltage applications.

One particular high voltage application is the generation of gas discharges, particularly in atmospheric air, which typically requires several kilovolts of input voltage. Corona discharges are one type of atmospheric-pressure gas discharge that utilizes highly inhomogeneous electric fields to constrict all of the ionizing collisions to the direct vicinity of one electrode. A corona discharge is generated when a large voltage difference exists between a sharp electrode, typically a wire, needle or a sharp edge, and a blunt electrode, usually a flat plate or a large cylinder. The non-uniform electric field near the sharp electrode allows for a localized high electric field region to form. When this electric field exceeds the breakdown field, an ionization zone forms around the electrode. The outer edges of this zone correspond to where the local electric field is below the breakdown field, which is ~3 kV/cm for atmospheric air [6].

The formation of a corona discharge produces a bulk flow often called an electrohydrodynamic flow or an ionic wind. Ions produced in the discharge are accelerated by the applied electric field and can collide with neutral air molecules, generating a bulk flow. Unlike mechanical fans, ionic winds are silent, require no moving parts and can be made to be miniaturized to operate in areas less than 1 cm [7]. These attributes have led to an increase in interest in using ionic winds to cool electronic devices [8]. However, to produce an ionic wind very large voltages need to be applied between two electrodes, typically on the order of ~5 kV [9]. To be a viable cooling method, new technologies need to be developed that will produce the large electric fields required to generate breakdown while being able to operate within the geometric confines of electronic devices.

By using the electromechanical coupling within piezoelectric transformers, it is possible to produce a large enough voltage gain to generate an ionic wind with input voltages less than 10 V. To achieve this, the surface of the piezoelectric is used as the counter electrode that exhibits a local high surface voltage when the material is subjected to mechanical displacement. In this work, the basic operating principles and device considerations of a piezoelectric-driven ionic wind are demonstrated and explored.

II. Device Configuration and Operation

Two different Rosen-type [2] piezoelectric transformers were built and tested in this study. The first transformer was built in a longitudinal orientation using a 100 × 15 × 1.5 mm 128° Y-cut piece of lithium niobate (LN). This particular rotation angle was chosen because it has been found to provide the optimum electromechanical coupling [10]. The LN crystal had a titatnium/aluminum (Ti/Al) electrode deposited on both of its faces, covering half of its length. The second transformer was built in a longitudinal orientation using a 53 × 7.5 × 2.6 mm piece of lead zirconate titanate (PZT) poled in the appropriate directions. The driving frequency of both transformers was chosen to match the second resonant mode of the crystal to allow for electrical energy to more efficiently convert into mechanical energy [11]. Driving the discharge at a resonance mode generates a standing mechanical displacement wave within the piezoelectric that must not be interfered with when mounted.

To secure and actuate the piezoelectric transformer, mounts in contact with the surface electrodes are placed at nodal points that correspond to zero displacement within the piezoelectric [12] such that they do not interfere with the mechanical displacement occurring as shown in Fig. 1. For the LN transformer, the AC signal was applied using two razor blades on opposite faces of the crystal in contact with the deposited Ti/Al electrodes. For the PZT transformer, a lead was attached to the piezoelectric with solder at the nodal point.

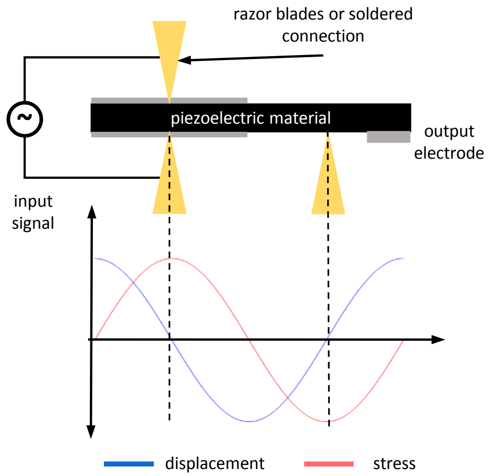

Fig. 1. A schematic of a piezoelectric transformer. The plot at the bottom shows the stress and displacement that occur within the piezoelectric when a standing wave forms at its second resonant frequency. The mounts for the transformer only make contact with the piezoelectric where the mechanical displacement is zero.

Typically, a lead is attached to the output electrode and then connected to the desired load. The same could be done in this situation, where the lead would be connected to a sharp electrode placed adjacent to a grounded, blunt electrode. However, it was found that this was not the most effective method of driving a discharge because coronas would still form on the piezoelectric transformer and would greatly reduce the efficiency of the system. To remove this mechanism of loss from the system, the piezoelectric transformer was used as either the blunt or the sharp electrode in the corona discharge, and two different configurations were employed as shown in Fig. 2. The two configurations differ in their use of counter electrodes, Fig. 2a uses an adjacent wire (copper, 0.002 in diameter) to generate the corona with the piezoelectric transformer serving as the blunt electrode while Fig. 2b uses the corners of the piezoelectric transformer itself as the sharp electrode.

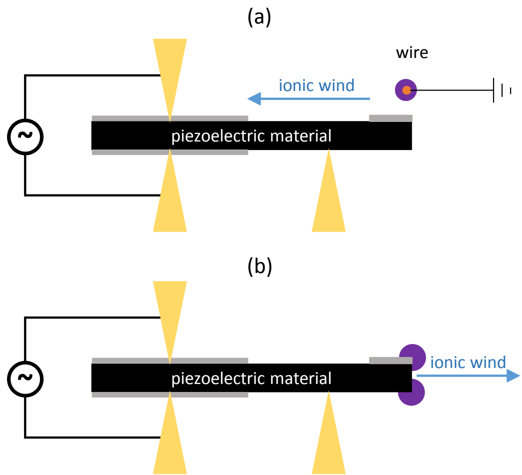

Fig. 2. Schematics of ionic wind generation with a piezoelectric transformer. (a) An adjacent grounded wire is used as the corona source and the piezoelectric transformer serves as a high-voltage blunt electrode. (b) The corners of the piezoelectric transformer serve as the corona source.

Figure 3a shows the glow that forms around the wire placed 0.5 cm from the surface of a LN crystal using the configuration shown in Fig. 2a. This image was taken when the transformer was driven at 7 V_{amp} input voltage, however a dimmer glow can still be seen at driving voltages as low as 5 V_{amp}. As the wire was moved further away from the piezoelectric surface, the glow became dimmer while corona discharges began to form on the edges of the crystal. Figure 3b shows these corner corona discharges when the wire was removed completely, corresponding to the configuration in Fig. 2b. These discharges become the brightest when the wire was absent or placed further than 1 cm from the piezoelectric surface. This shows that during operation, the piezoelectric surface exhibits a very high electric field, enough to locally breakdown air. When the wire is placed near the piezoelectric surface, ions are produced in the discharge that forms in the high electric field region generated by the wire. These ions move to the surface of the piezoelectric and screen the electric field at the piezoelectric surface. When the wire is moved further from the piezoelectric, fewer ions reach the piezoelectric surface from the wire allowing the piezoelectric to form discharges at its own edges.

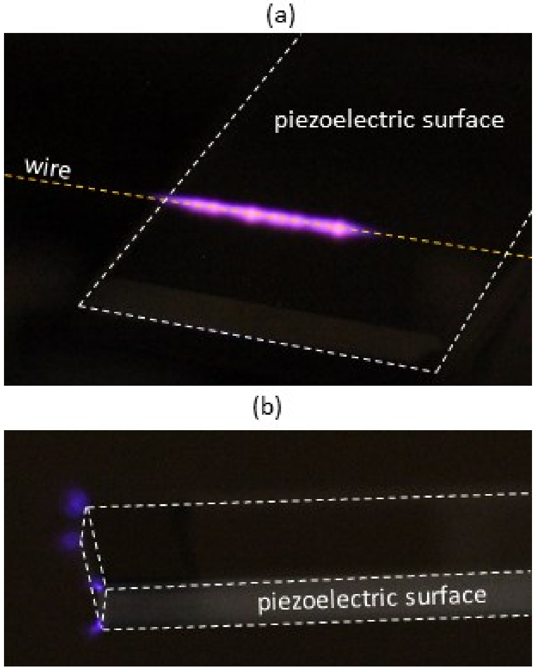

Fig. 3. (a) The glow that forms around a grounded wire when placed 0.5 cm from the surface of a LN piezoelectric transformer. (b) The glow at the corners of the LN piezoelectric if the grounded wire is removed. The transformer was driven with a 7 V_{amp}, 60.3 kHz sine wave for both images.

III. Ionic Wind Generation

To demonstrate the generation of an ionic wind by a piezoelectric transformer, a duct was constructed that would allow for a PZT piezoelectric transformer to be placed flush within one of the duct walls, as shown in Fig. 4a. The duct was 2 × 5 × 18 cm and built so that the piezoelectric transformer in the wall can be replaced by a copper plate of the same dimensions to allow for comparison between a piezoelectric-driven discharge and a standard AC corona discharge using two meal electrodes. A thin copper wire was placed 5 mm above the very edge of the PZT transformer and attached to ground. A hot wire anemometer was placed at the outlet of the duct and used to measure the wind speed. Figure 4b shows the measured ionic wind speed for different applied voltages using the piezoelectric transformer as well as using only metal electrodes (replacing the piezoelectric transformer with a copper plate) for comparison. Using the piezoelectric transformer reduced the voltage required to generate an ionic wind by two orders of magnitude. To produce a flow velocity of 0.3 m/s, the PZT piezoelectric-driven ionic wind only required 20 V_{amp} input while the standard AC corona discharge required nearly 6000 V input voltage. This demonstrates the great promise for piezoelectric-driven ionic winds by removing a very large obstacle for their use in many applications.

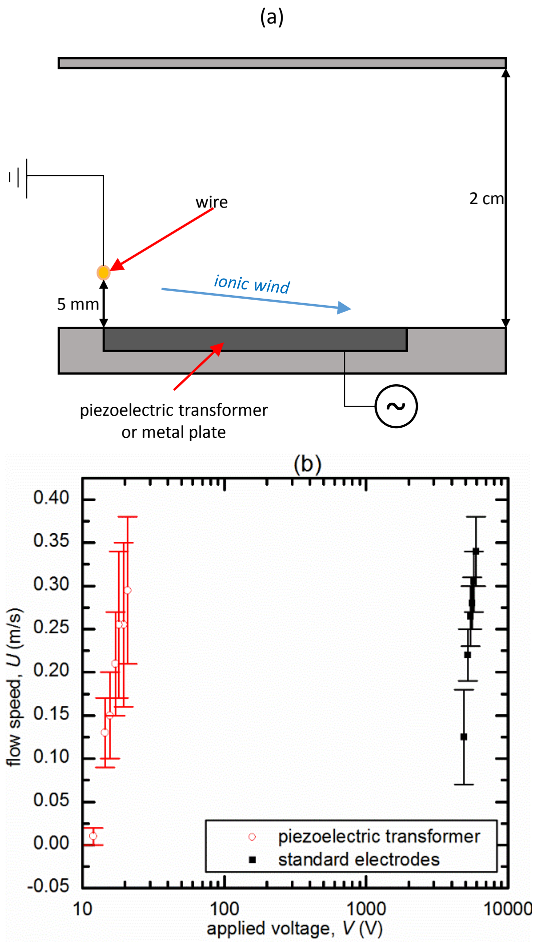

Fig. 4. (a) A schematic of the duct used to measure the speed of the induced ionic wind generated from PZT and a standard metal electrode. (b) Measured wind speed at different input voltages for the two configurations.

An alternative method of ionic wind production was also achieved without the need for an adjacent grounded wire. The LN piezoelectric transformer was mounted within a 1 $\times$ 10 $\times$ 2 cm duct attached to a flow bench as shown in Fig. 5a. Using this configuration, the ionic wind generated by the coronas on the edges of the piezoelectric were measured. Figure 5b shows the flowrate generated for different input voltages. Remarkably, using the LN piezoelectric transformer allowed for ionic winds to be measured at voltages as low as 10 V_{amp}. While these results are promising, there is still a large amount of optimization that can be done to further improve the system. The razor blades used to mount the piezoelectric and apply the input signal were positioned in such a way that air could move through them and into the duct. It is reasonable to assume that the presence of these razor blades at the opening of the duct attributed a non-negligible amount of pressure loss, reducing the effectiveness of the induced ionic wind. More work needs to be done on developing an alternative mounting apparatus that can hold the piezoelectric in place while minimizing interference with the produced ionic wind. Further work will look into modifying the geometry of the piezoelectric itself to promote discharge production at the center of the duct [13].

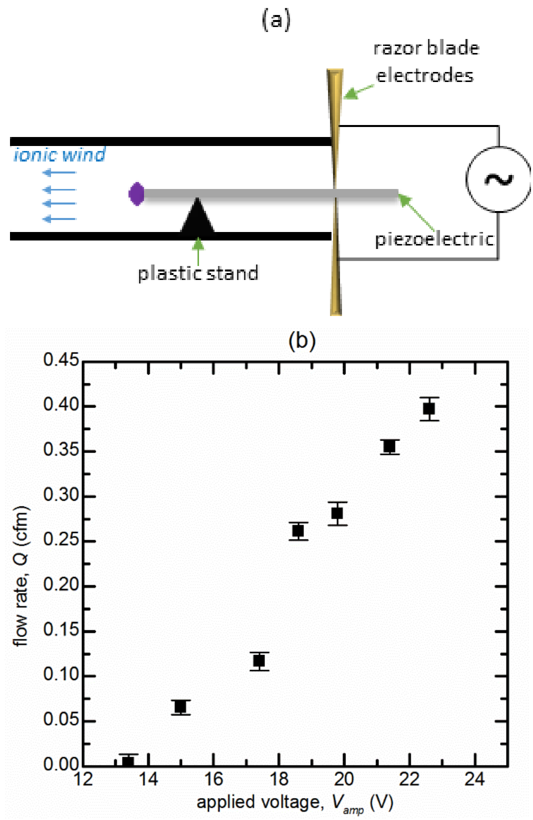

Fig. 5. (a) Schematic of the duct used to generate an ionic wind from the coronas on the coroners of a piezoelectric transformer driven at its resonant frequency. The flow rate induced from the piezoelectric-driven ionic wind device in duct with (b) varying applied voltage.

To improve the flow production from the piezoelectric transformer, the walls of the duct downstream of the transformer were covered with copper electrodes and grounded, as shown in Fig. 6a. By adding a grounded electrode downstream of the piezoelectric, the ions generated in the discharge will feel the electric field produced by the grounded electrode and should be more likely to travel in that direction. Figure 6b shows the measured flow velocity with and without the downstream electrode as a function of the driving frequency of the input voltage. The flow velocity is a strong function of the driving frequency because the transformer must be run at its resonance frequency in order to produce a large enough voltage gain to generate a discharge. Without the downstream electrode, the flow velocity hit a peak at 60.325 kHz and quickly decreased as the frequency was changed. Unexpectedly, the resonance frequency of the piezoelectric transformer was altered when the downstream electrodes were put into place. In order to generate a flow, the driving frequency had to be changed once with the downstream electrodes to match the new resonance frequency. Even when run at its resonance frequency, the downstream electrodes decreased the maximum flow velocity from the piezoelectric transformer.

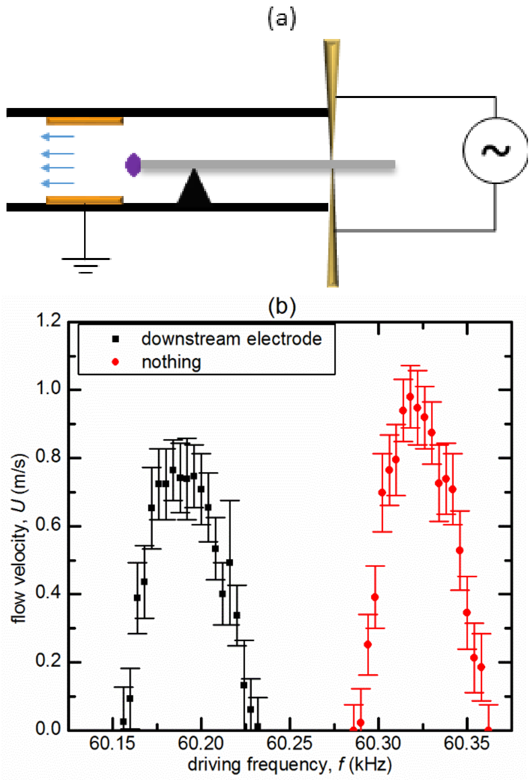

Fig. 6. (a) Metal electrodes were placed downstream from the piezoelectric transformer to improve flow production. (b) The flow velocity as a function of frequency with and without the downstream electrodes.

To better understand the effects of altering the operating configuration by adding downstream electrodes, a simple circuit was developed, shown in Fig. 7a, where the values of each parameter are listed in Table 1. Figure 7b shows the resonance frequency and the max output voltage for different output capacitances. The resonance frequency was defined as the frequency that produced the largest $V_{out,max}$ while the normalized voltage was the V_{out} divided by the maximum $V_{out,max}$ for all capacitances. For corona discharges, the flow velocity of the induced ionic wind is proportional to the voltage of the electrode [7]. This relationship allows us to attribute the decrease in flow rate with the downstream electrode shown in Fig. 6b to a decrease in the voltage gain in the piezoelectric transformer, which is shown in Fig. 7b. The downstream electrode acts as an additional capacitor in parallel with C_{out}, causing the total output capacitance to increase. Figure 7b shows that an increase in the output capacitance of the piezoelectric transformer can lead to both a decrease in the resonance frequency and a decrease in V_{out}, which qualitatively matches observations from the ionic wind measurements. With this circuit, we can investigate the effects of capacitance have on different piezoelectric materials. Figure 7c shows the resonance frequency for various different output capacitances for the PZT and LN. It is important to note that the values used for the LN circuit were obtained from matching the resonance frequency of the LN transformer and are not experimentally found values. Therefore the circuit can only be used to qualitatively illustrate how it varies with capacitance without exact values. In experiments, adding an electrode downstream from the PZT transformer had a much smaller impact than what occurred with LN, which is consistent with the results from the model circuit shown in Fig. 7c. This shows that the performance of the piezoelectric-driven ionic wind is a function of its surroundings, which need to be accounted for when designing a device.

TABLE 1: VALUES FOR DIFFERENT ELECTRIC COMPONENTS IN MODEL CIRCUIT [12]

Parameter	LN values	PZT values*
C_{in}	0.2 μF	710 pF
L_1	1 mH	158 mH
C_1	6 nF	35 pF
R_1	2 Ω	43 Ω
T_1	1:300	1:300
R_{out}	1 $M\Omega$	1 $M\Omega$

*provided by the manufacturer

IV. CONCLUSION

In this work, it was shown the electromechanical coupling present within a piezoelectric can be used to generate an ionic wind with low applied voltages. During operation, the piezoelectric exhibits a large surface voltage, allowing for discharges to be generated on adjacent electrodes or directly on its surface. This allows for several different configurations to be used to generate an ionic wind. Due to the large voltage gain provided by the transformer, ionic winds have been generated at voltages as low as 5.5 V. However, the voltage gain provided by the piezoelectric transformer is a strong function of its surroundings requiring careful design when developing a device. The low voltage operation and its small size make the piezoelectric-driven ionic wind an attractive alternative to current electronics cooling technology.

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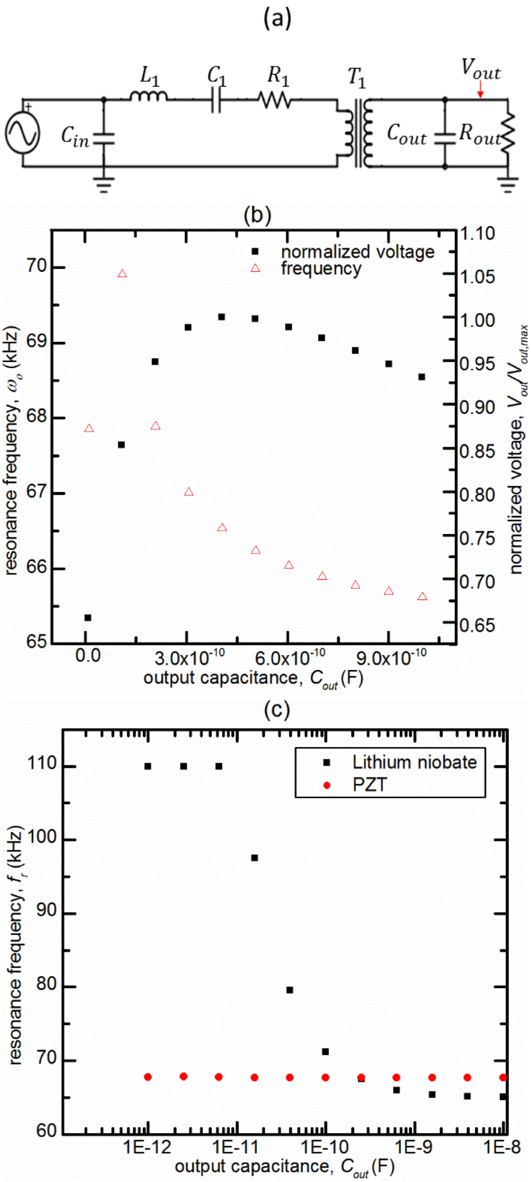

Fig. 8. (a) Model circuit used to simulate the effects on the piezoelectric transformer when the output conditions are changed. (b) Predicted resonance frequency and the normalized voltage of a LN transformer as the output capacitance is varied. (c) Comparison between the resonance frequency of PZT and LN for different output capacitance.

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