

Studying the effects of temperature on energy harvesting using pre-stressed piezoelectric diaphragms

Poorna Mane^{*a}, Karla Mossi^a, Christopher Green^a, Robert Bryant^b

^aDept. of Mechanical Engineering, Virginia Commonwealth University, 601 West Main Street,
Richmond, VA, USA 23284;

^bNASA Langley Research Center, MS 226, Hampton, VA, USA, 23681

ABSTRACT

Energy harvesting is a process in which energy which would otherwise be wasted is captured, stored and then used to power a system. Devices having such capabilities enjoy an extended life particularly advantageous in systems with limited accessibility, such as biomedical implants and structure embedded micro and wireless sensors. A viable family of materials for this purpose is piezoelectric materials because of their inherent ability to convert vibrations into electrical energy. This paper uses a type of pre-stressed PZT-5A Unimorph called Thunder[®], to actively convert mechanical vibrations into useable power. The effects of temperature, 20-100°C, pressure, 138-345kPa, frequency, 2-5Hz, and load resistance, 0.47-2.0MΩ, on the energy harvesting potential of the device are studied. The data obtained is analyzed using statistical techniques that assess the significance of the factors being studied. Results showed that the effect of temperature by itself on the voltage, AC or DC, and power generation was seen to be not significant. In combination with other factors such as pressure, frequency, and load resistance however, the temperature effect becomes statistically significant. These interaction effects tend to reduce voltage and power conversion. The maximum DC voltage and power were calculated as 108V and 11641μW at 20°C, 275.8kPa, 2.5Hz and 2MΩ. Similarly the greatest peak to peak AC voltage of 338V was also measured at 20°C and 2.5Hz. Based on the geometry of the piezoelectric diaphragm the most power density was evaluated to be 15μW/mm³.

Keywords: pre-stressed, energy harvesting, Thunder[®], piezoelectric, regression analysis

1. INTRODUCTION

Renewable energy sources, which can be defined as “energy flows which are replenished at the same rate they are used”, have become attractive alternatives¹. Energy conversion, which is the process of converting energy from one form to another, is subject to the law of energy conservation which states that the total energy within a closed system is constant. However, in a large physical system where friction is present some of this energy will be deemed useless or even detrimental to the system. This energy takes the form of heat, vibration, and sound and is calculated as a loss. Scavenging this type of energy to boost a system’s efficiency is a growing area of interest.

One potential application lies in the powering of portable wireless devices. The problem with wireless technology is that receives and transmits at higher power densities relative to the battery power. For an application such as health condition monitoring, a wireless sensor must be on at all times. The long life argument breaks down when the application is constantly “on” making constant system monitoring impractical. Examples of this are the vibration monitoring of a bridge under constant stress or a motor under load. In harsh or remote environments the frequent changing of batteries may not be feasible. Thus, batteries have life spans that are often at odds with the practical needs of modern electronics thus creating a need for alternative power sources either as a supplement or a substitute.

To that end, technologies that utilize new materials capable of generating and transmitting energy are being investigated. A viable family of materials for this purpose is piezoelectric materials because of their inherent properties. Piezoelectric devices are self-generating, and since vibrations occur in most dynamic systems, these materials have wide dynamic range, and have low output noise. Roundy et al. have shown that a power density of 70μW/cm³ is quite feasible from a PZT bimorph beam mounted as a cantilever. Simulations by the same investigators show that an optimized design

would be capable of $250\mu\text{W}/\text{cm}^3$ from a vibration source with input vibrations of 2.5m/s^2 at 120Hz ^{2,3}. Erika et al. modeled and tested a Unimorph membrane consisting of PZT and brass encircled by an aluminum ring⁴ mounted on a mechanical shaker. The excitation of the shaker was varied between 0-5g of acceleration. The electrical output of the membrane was connected to load resistors which varied from 100Ω to $1\text{M}\Omega$. It was found that a maximum power of 1.8mW was generated at an acceleration of 2g with a $56\text{k}\Omega$ load resistance. Yoon, Washington, and Danak studied the charge generation properties of curved rectangular PZT Unimorph beams by optimizing the design parameters⁵. A shoe insert which was used in a previous study to harvest energy while walking, was modeled using the piezoelectric constitutive equations and the shallow, thin shell theory. An equation was derived that expressed charge generation of the PZT beam in terms of applied force, material properties and geometry. In a parametric study using the dimensions from nine samples, it was shown that geometry and material properties do affect charge production. Increasing the width, center height, and the thickness of the substrate produces increased charge generations. During this study, an experiment was conducted by dropping a 5lb weight on a sample and determining its charge production. Another experiment was conducted by determining the charge production of a sample by while a 100lb human stepped on it.

The electrical charge generated from a piezoelectric device is usually insufficient to power a commercial sensor but by rectifying and regulating the signal a usable voltage can be applied to the sensor directly or used to charge a battery⁶. The type of circuitry used to harvest the energy from a piezoelectric transducer is determined by the desired output to the load which most often needs to be rectified, filtered, and regulated⁷. A piezoelectric transducer can be modeled as an AC source in parallel with a capacitor. To convert this signal into a useful one, an AC-DC converter is used to rectify the AC signal. The output from this converter is then sent to a DC-DC converter where it is regulated to the desired voltage. Roundy et al. explored the possibility of scavenging low level vibrations as a power source for wireless sensor nodes. In this study, the geometry of the piezoelectric device was optimized while the load resistance of the circuitry, which consisted of a series inductor with an active bridge, was varied. A piezoelectric generator was modeled as an AC source in series with a capacitor, and a resistance^{2,3}. Other approaches include the use of piezoelectric composites. Sodano, Lloyd, and Inman for instance, compared the ability of a three different types of composites to convert mechanical strain into electrical energy by exciting them while attached to an aluminum beam. Their study concluded that impedance matching between the transducer and the circuit is critical when optimizing for power^{8,9}.

Mossi et al. performed an investigation of parameters that affect actuation and energy harvesting on rectangular pre-stressed piezoelectric Unimorph¹⁰. Parameters such as conductivity of the adhesive, composition, size, type and thickness of the layers, were investigated using fractional factorial experimental design techniques. Statistical analyses of all the results were performed to determine the significance of the parameters tested. The study concluded that circuitry must be coupled with device geometry to optimize its performance.

An extensive literature review indicates that all previous studies on energy harvesting have all been performed at room temperature although most of the thought of applications could have differing environmental conditions. Very little research has been done using pre-stressed piezoelectric devices under temperature even though they have been proven to have enhanced strain capabilities¹¹. For this reason, the purpose of this work is to study the effect of temperature on the harvesting of vibration energy scavenged from a clamped circular piezoelectric pre-stressed diaphragm by applying dynamic, pressure loading. This setup is explained in the following section.

2. EXPERIMENTEL SETUP

2.1 Thunder[®]

The piezoelectric device used in this study is called Thunder[®]. Thunder[®] is a pre-stressed composite of PZT-5A sandwiched between a top and bottom layers of dissimilar metals bonded with a high temperature polyimide adhesive (SI)¹². The sandwich is assembled and then heated to 325°C under vacuum. During cooling, the different coefficients of

thermal expansion of the dissimilar metals cause the curved shape that is unique to Thunder[®] devices. The bottom SI layer between ceramic and steel contains conductive inclusions which have been shown to enhance the energy harvesting properties^{10,12}. Thunder[®] devices were chosen for this study because of their rugged construction and high performance when used as an actuator and a sensor¹³. Thunder[®] devices come in various shapes and sizes. The type of Thunder[®] used in this study was a circular diaphragm in which the top layer of metal was type 102 copper that had been perforated through chemical etching to change its stiffness. The bottom layer of metal was type 302 stainless steel. The piezoelectric layer is a PZT-5A with a material type of 3195HD manufactured by CTS Communications Components, Inc. The exact geometry is described in Table 1. Figure 1 shows different views of the device describing its layer composition.

Table 1. Overall geometric parameters

Thickness (total)	0.68mm (0.0295in)
Thickness (ceramic)	0.25mm (0.010in)
Diameter (total)	66.12mm (2.60in)
Diameter (ceramic)	61.72mm (2.44in)
Weight	14.5g (0.509oz)

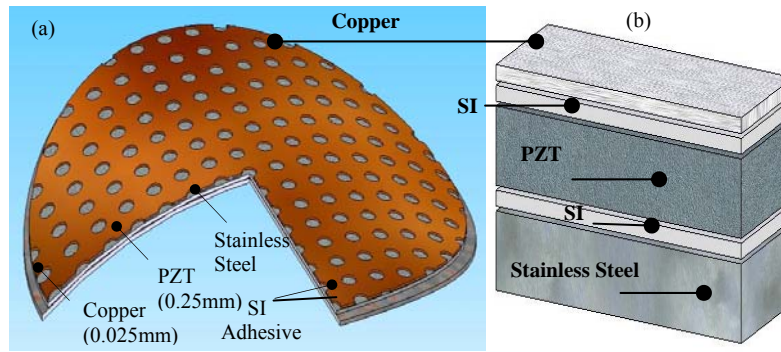


Figure 1. Circular Thunder[®] Diagram (a) Cutaway; (b) Layers

2.2 Pressure and Temperature Setup

A block diagram of the experimental setup is shown in Figure 2. To actuate the Thunder[®] device, approximately 758.43kPa (110psi) of clean dry air (CDA) was sent to a model 42K75 regulator/filter combination manufactured by SpeedAire with a 0-827.4kPa (0 - 120psi) pressure gauge. The regulated pressures used during this study were 138kPa (20psi), 206.85kPa (30psi), 275.8kPa (40psi), and 344.75kPa (50psi). During initial testing it was found that the limits of the flow meter were reached at a dynamic pressure of 50psi (344.75kPa) so this value was set as the upper pressure limit of the experiments. The lower limit was set according to the minimal voltage production needed by the application. This air was then sent through an Omega FMA 1609A flow meter which measured mass and volumetric flow rate, temperature, and absolute pressure of the air entering the pressure chamber. A view of the Thunder[®] diaphragm and the pressure housing is shown in Figure 3. The pressure housing was fabricated at NASA Langley Research Center and is made of aluminum. Air was routed using a Parker three-way valve that was powered by 120VAC. The first port on the three-way valve was 758.43kPa (110psi). The second port was vented out into the atmosphere and the third port was output to the pressure cavity. The valve was switched on and off using an adjustable timer manufactured by National Controls Corporation model TMM-0999M-461. The frequencies (2.5Hz, 3.25Hz, and 5Hz) used in this study were determined by the dynamic limitations of the 3-way valve. This switched air was then routed to the pressure chamber. One end of the cavity is enclosed while the other has a slot that is open to the atmosphere. The Thunder[®] actuator was clamped around its outer edge by the chamber. The pressure housing was enclosed in an environmental chamber from

Sun Systems Model EC1.3W capable of heating up to 350°C. While in the chamber the diaphragm can be heated to desired temperatures.

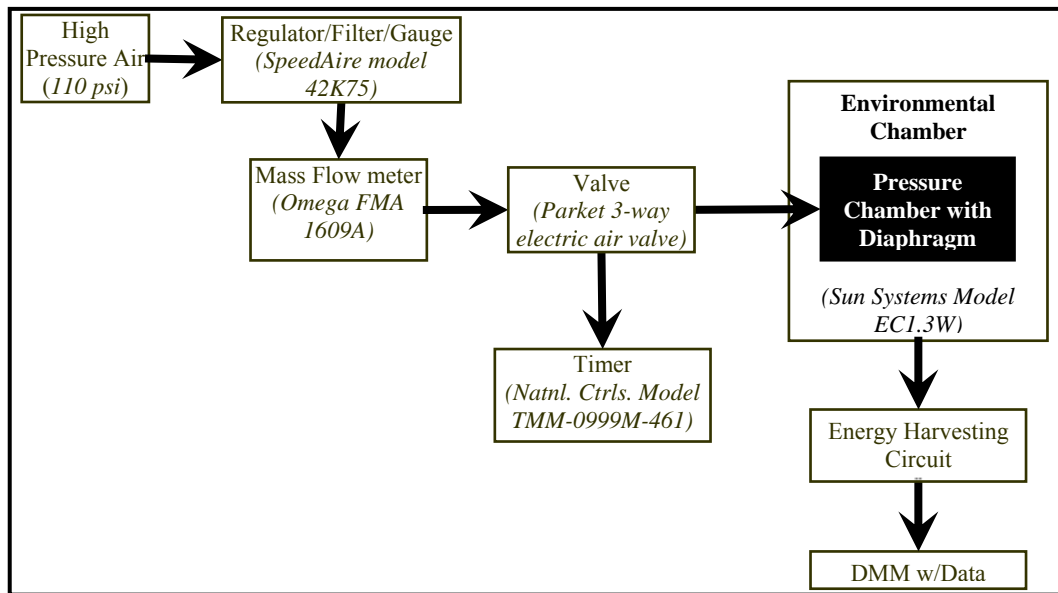


Figure 2. Experimental setup

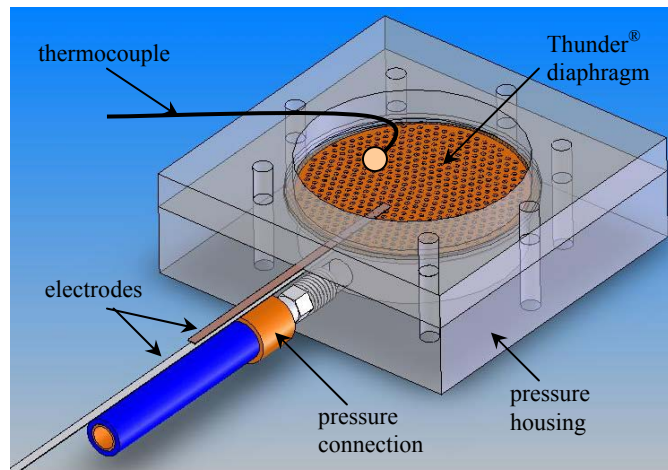


Figure 3. Pressure chamber with Thunder® diaphragm

2.3 Energy Harvesting Circuit

The passive rectifier circuit was chosen as the energy harvesting circuit because of its simplicity and lack of active components which consume power. A schematic of the circuit is shown in Figure 4. The first stage of the circuit which is in parallel with the Thunder® diaphragm is a RB114 Full Wave Bridge Rectifier. A Full Wave Bridge Rectifier converts AC to DC using a system of four diodes (D1) arranged such that the polarity in is the same as the polarity out. Each time a signal travels through the diode network; there is a voltage drop that depends on the characteristics of the diode. When attached to a load, marked at R1 in figure, the negative part of an input sine wave is removed and the frequency is increased by a factor of two. Theoretically, the output DC voltage should be 63.6% of the value of the input peak to peak

voltage. The output DC voltage deviates from a constant DC voltage by a parameter called a ripple voltage. When a capacitor is added, as represented by C1 in Figure 2, ripples are smoothed and transients are filtered¹⁴.

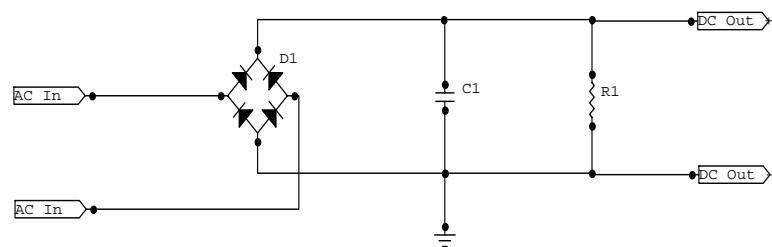


Figure 4. Energy harvesting circuit

Initially the peak to peak AC voltages for each pressure and frequency were measured at various diaphragm temperatures and acquired using a Tektronix TDS2024 oscilloscope and Labview[®] software. In the second experiment a load resistor, a 4.7μF capacitor and a rectifier were added forming an AC-DC converter. The DC output was then measured. In the final experiment capacitors were added to the rectifier and load resistors. The output DC voltage of the energy harvesting circuit was measured over a time interval to observe the charging and discharging behavior of each circuit. One of the aims of the final set of experiments was to calculate the total and discharge energy delivered to the load during a given time interval. Charging energy was not taken into account because of the timing limitations of the measurement device. Table 2 shows the characteristics of each experiment.

Table 2. Summary of experiments

	Pressure	Frequency	Temperature	Rectifier	Capacitor	Load Resistance	Output
Experiment 1	X	X	X				ACV
Experiment 2 (Measured over time)	X	X	X	X	X	X	DCV

From the collected data of all experiments, values of voltage, powers, and energy, are studied to make a determination about the energy generating characteristics of Thunder[®] diaphragm. A matrix of the experimental parameters is shown in Table 3.

Table 3. Experimental parameters

Frequency	2.5Hz 3.25Hz 5.0Hz
Pressure	138kPa (20.0psi) 206.85kPa (30.0psi) 275.8kPa (40.0psi) 344.75kPa (50.0psi)
Temperature	20°C 40°C 60°C 80°C 100°C
Resistance	470kΩ 1MΩ 2MΩ

3. RESULTS

The paper involves the study of a number of factors at several levels affecting a common response of voltage or power. The experimental results are presented in the following sections and statistical analysis is used to determine the significance and impact. The correlation coefficient (R^2), the p-value, and the F-value are used to determine correlation and significance of the different parameters.

The first experiment consisted on measuring the open circuit voltage, which is the voltage with no load, of the Thunder[®] diaphragms. The diaphragms were actuated at pressures ranging from 138kPa to 345kPa with frequencies of 2.5Hz, 3.25Hz, and 5Hz for each pressure. For each pressure - frequency combination the waveforms were captured at different diaphragm temperatures from 20°C to 100°C using a storage oscilloscope. Figure 5 shows a typical curve at 20°C and 100°C curves at 5Hz and 345kPa pressure. Other curves have been omitted for clarity. The region marked *a* in figure is the maximum voltage section for 20°C and corresponds to the maximum deflection position of the diaphragm similarly the region marked *a'* is the maximum voltage section for 100°C. The regions marked *b* and *b'* correspond to the rest position of the diaphragm. Both curves have different shapes indicated by the marked regions and at different pressures the pattern persists. While the voltage peaks at 20°C a flat section is seen at 100°C. This difference in the ac voltage curves could be related to the stiffness of the piezoelectric diaphragm. In a study conducted by Mossi et al. the stiffness of rectangular Thunder diaphragms was studied at temperatures ranging for 20°C to 120°C. Their observations lead to the conclusion that stiffness of the diaphragm increased sharply at 40°C followed by a decrease at subsequent temperatures¹⁴.

Figure 6 shows the positive and negative peak voltage for the specific case of 2.5Hz at two pressures with changing temperatures. For clarity, other curves are removed. Note that peak positive AC voltages are larger than the peak negative voltages. This may be due to the shape and positioning of the device in the cavity. When pressure is applied, the diaphragm is pushed, and when the pressure is released, the diaphragm comes back to its rest position which is maintained constant. The positive and negative peak voltages for each pressure, frequency and temperature combination were processed in order to determine the effects of temperature within the scope of this study. The data indicate that temperature has a negative effect on the generated voltage with certain exceptions, suggesting that the interaction of temperature with other factors may also be affecting the output. To further investigate these interactions voltage at increasing pressures is plotted in Figure 7. In this case the peak to peak output voltage appears to increase. The maximum peak to peak voltage of 338V was measured at 20°C, 2.5Hz and 345kPa. As the results are inconclusive and a clear pattern does not emerge further analysis is required which is possible through statistical techniques.

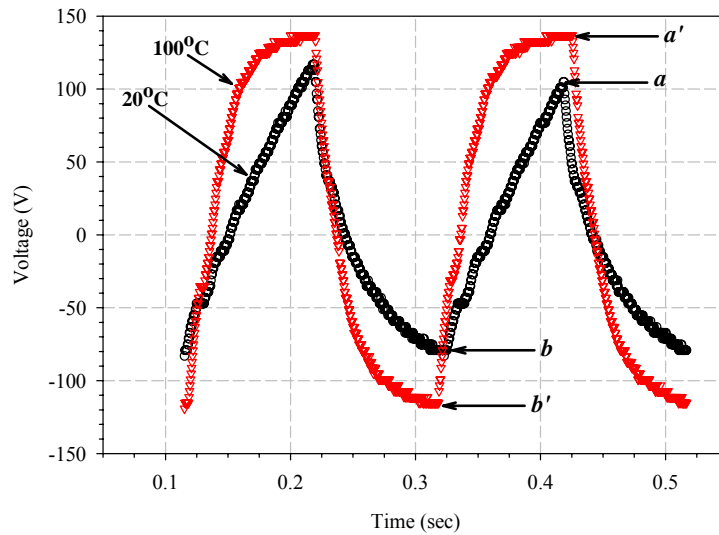


Figure 5. AC voltage curves at 5Hz and 345kPa

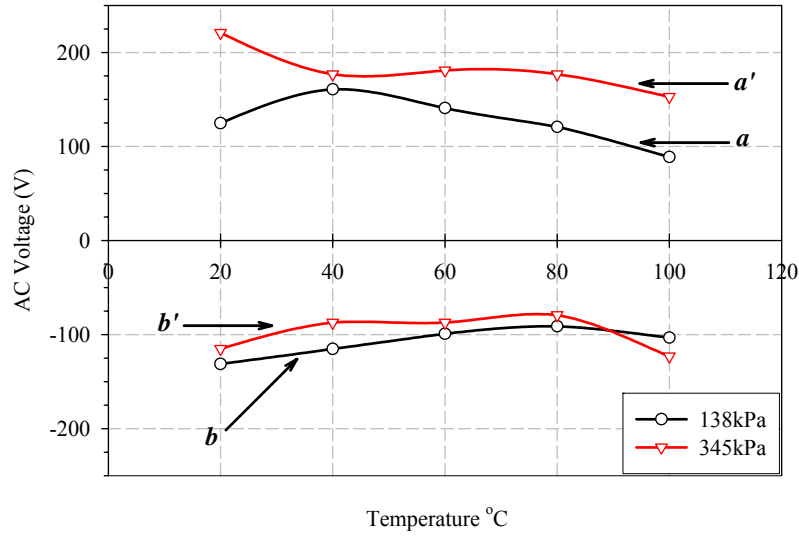


Figure 6. Positive and negative peak voltages at 2.5Hz

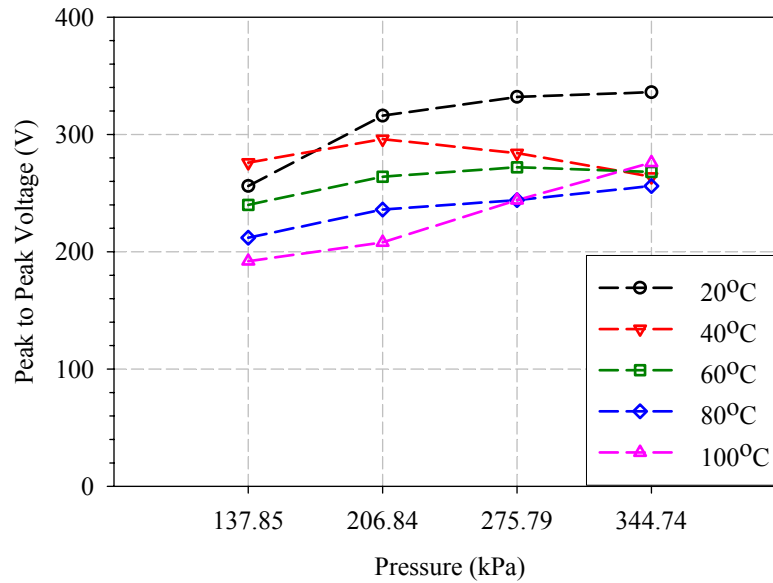


Figure 7. Pressure effect summary at 2.5Hz

To further explore the factor interactions observed in the initial analyses a regression analysis of the experiment was performed. A subset of regressions based on the form shown in Equation 1, were tested by evaluating the p-value of each parameter or its significance.

$$V = \beta_0 + \beta_1 \cdot f + \beta_2 \cdot p + \beta_3 \cdot T + \beta_4 \cdot (fp) + \beta_5 \cdot (fT) + \beta_6 \cdot (pT) + \beta_7 \cdot (fpT)$$

Equation 1

The three main factors of temperature (T), pressure (p) and frequency (f) were included in the analyses along with all the second and third level interactions between them. The second level interactions were frequency – pressure (fp),

frequency – temperature (fT), and pressure – temperature (pT) with one third level interactions existing between the main factors (fpT). A 95% confidence interval is defined for the regression and an interpolated empirical model is obtained for the response variable (generated ac voltage output, V). The final subset of this equation and its coefficients are shown in Equation 2.

$$V(AC) = 242.18 + 26.14 \cdot f + 6.85 \times 10^{-4} \cdot p - 2.58 \times 10^{-4} \cdot (fp) - 0.59 \cdot (fT) - 5.88 \times 10^{-6} \cdot (pT) + 3.19 \times 10^{-6} \cdot (fpT)$$

Equation 2

Where the V is AC, f is in Hz, p is in Pa, T is in °C. This regression indicates the heavy influence of both second and third level interactions on the response but not a direct influence of temperature. While the main effect of temperature is not significant by itself in combination with pressure and frequency it has a large effect on the output. The negative coefficient of the second level terms containing temperature, points to the detrimental effect of this property on voltage generation. In contrast with the coefficient found for the frequency that is larger than the other values, frequency has a positive effect on generated AC voltage. Figure 8 shows a contour plot of the fitted data with the two main factor effects of frequency and pressure. The curved lines are lines of constant voltage that indicate the presence of interaction effects. In general the voltage generated is increased at higher pressures and frequencies. This can be explained by the strong correlation between pressure and diaphragm deflections and between deflection and voltage seen by Green during his studies¹².

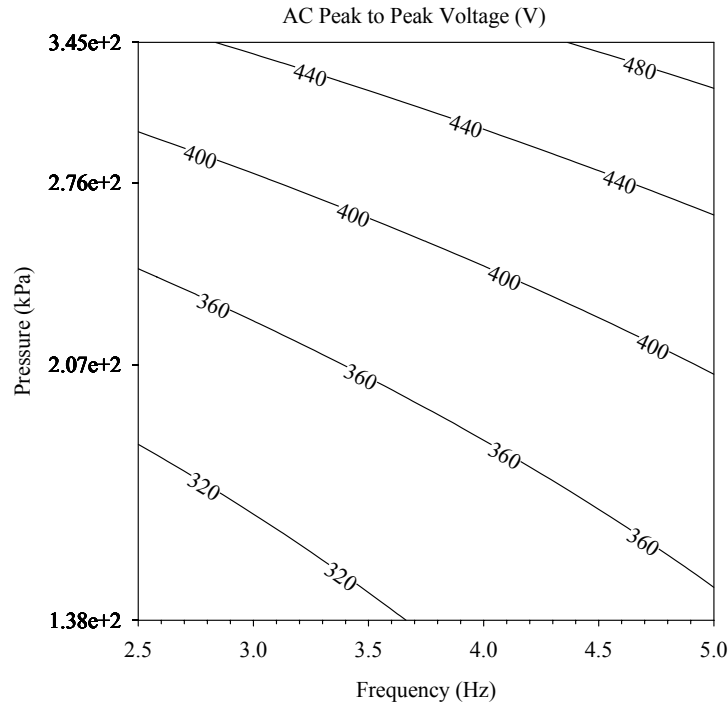


Figure 8. A contour plot of the regression model for the effects of pressure and frequency at constant lines of ac peak to peak voltage

The second sets of experiments consisted on measuring voltage with the Thunder[®] diaphragm connected in parallel to a full wave rectifier, a resistive load and a capacitor. The connected circuit converts the AC output to a DC voltage. Since AC voltage cannot be used to power most applications, a load is connected to test the capabilities of this system for power generation. The load resistances used in this experiment were varied from 470kΩ to 2MΩ and the capacitor had a value of 4.7μF. The purpose of the capacitor was to provide filtering and energy storage. The capacitor value was chosen based on previous studies conducted by Green where a 4.7μF capacitor generated the highest power¹². Voltage generated was recorded at different loads and repeated at all temperatures, pressures and frequencies combinations.

Typical DC voltage curves with time are shown in Figure 9. The curves demonstrate charging and discharging of the capacitor at different temperatures. The voltage data was collected over time with the aim of calculating energy delivered to the load. Power was calculated by dividing the square of the voltage data by the load resistance. The maximum DC voltage recorded was 108V at 20°C, 275.8kPa, 2.5Hz and 2MΩ. The maximum power was also recorded at the same conditions as 11641μW or a power density of 15.3μW/mm³. Calculating the area under the power – time curve (similar to figure 9 not shown due to space restrictions) gives the total energy over time which was found to be 1.36 J.

Initial observations of this set of experimental results do not indicate an easily identifiable trend. Having four factors in the experiment makes it necessary to use similar statistical techniques employed in the first experiment. In this case there are four main factors of temperature (*T*), pressure (*p*), frequency (*f*) and resistance (*r*). As in the previous case second and third level interactions are considered such that there are 14 factors in all. Equation 3 gives the linear regression fit of the dc voltage data.

$$V(DC) = 28.41 + 8.98 \cdot f + 3.61 \times 10^{-5} \cdot r + 7.18 \times 10^{-5} \cdot p - 3.12 \times 10^{-6} \cdot (fr) - 9.60 \times 10^{-2} \cdot (fT) - 4.33 \times 10^{-5} \cdot (fp) - 1.18 \times 10^{-7} \cdot (rT) + 4.71 \times 10^{-7} \cdot (fpT)$$

Equation 3

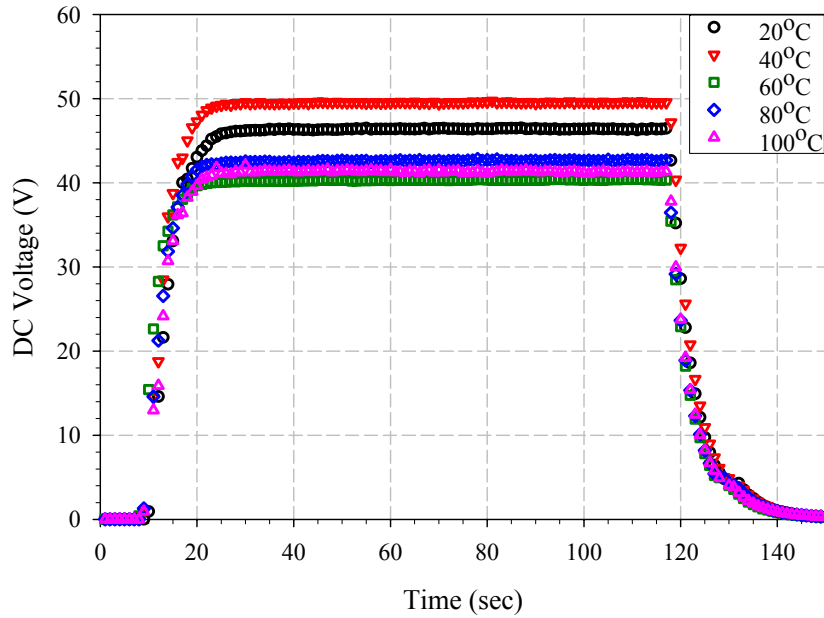


Figure 9. Typical DC Voltage curves at 2.5Hz and 470kΩ

The model indicates that temperature does not have a direct effect on the voltage. In interaction with other factors temperature has a negative effect leading to lower power generation. Equation 3 is similar to Equation 2 with the addition of one factor (resistance '*r*'). Load resistance has a considerable effect on the voltage with higher resistances generating higher voltages. This observation agrees with our previous observation of maximum voltage and power measurements at 2MΩ. The contour plots shown in Figure 10(a) and (b) indicate that both pressure and resistance influence the voltage positively. The curved lines show the presence of interaction effects. These graphs further highlight the similarity of the two regression models discussed in this study.

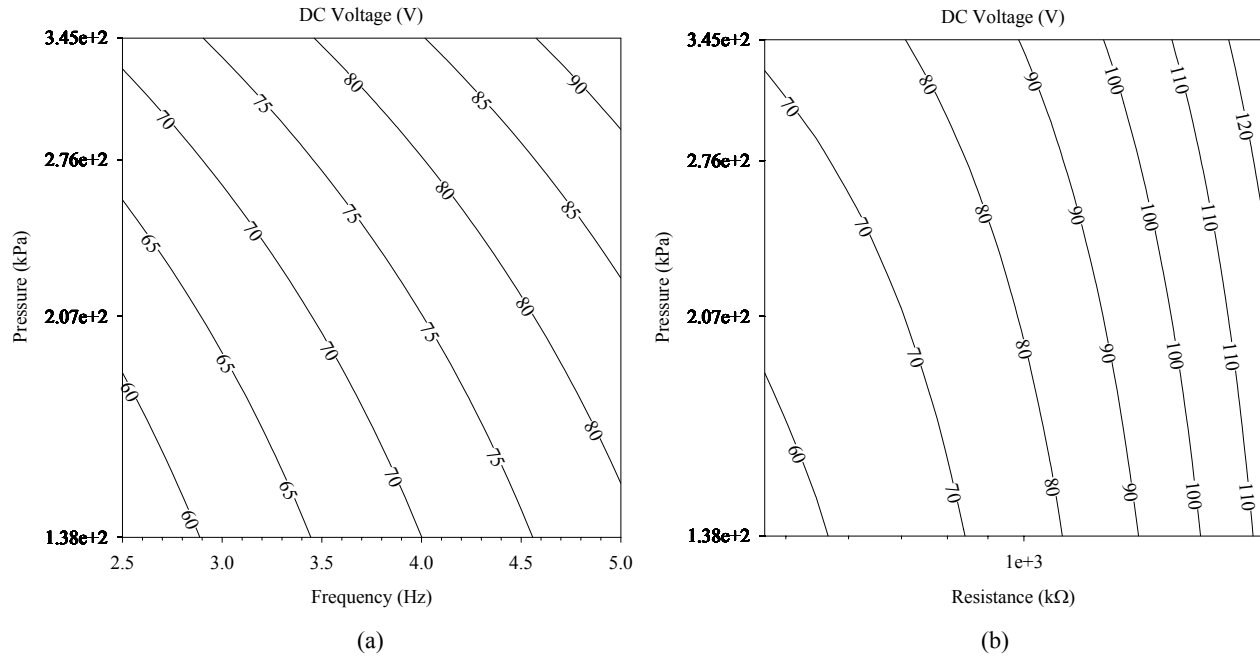


Figure 10. Contour plots of the regression model at constant lines of dc voltage (a) effects of pressure and frequency, (b) effects of pressure and resistance

4. CONCLUSIONS

The effect of temperature on the energy harvesting property of a prestressed piezoelectric Thunder® diaphragm is studied. The diaphragm is vibrated at various frequencies and temperatures using a pressure setup. In the first part of the study the AC voltage output by the device is measured while in the second part a circuit is connected in parallel with the device to convert the AC voltage to DC. A load and a capacitor are also added in the circuit to study the power and energy dissipation capabilities of the device. In both phases of the study, the temperature effects were not clearly demonstrated. To provide some more insight in the role of temperature, pressure, frequency and load statistical techniques that utilize multiple regression analysis of the different factors was utilized. The models developed for both cases show that temperature alone does not have a significant effect on the output voltage. However the interaction of temperature with other factors such as pressure, resistance and frequency effects are significant. The coefficients in the models indicate that temperature has a negative effect on the output while pressure, resistance and frequency have a positive effect. The maximum DC voltage and power were calculated as 108V and 11641 μ W at 20°C, 275.8kPa, 2.5Hz and 2M Ω . Similarly the greatest peak to peak AC voltage of 338V was also measured at 20°C and 2.5Hz. Based on the geometry of the piezoelectric diaphragm the most power density was evaluated to be 15 μ W/mm³.

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