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# Effect Of Temperature On A Piezoelectric Mass Flow Rate Sensor Signal

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EFFECT OF TEMPERATURE ON A PIEZOELECTRIC MASS FLOW RATE SENSOR SIGNAL

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## Dedication

For

My family who has been there for me in all the tough and important moments of my life. This accomplishment is thanks to your effort, the guidance and support that you have provided to me throughout my life. Everything that I have and the person that I am at this moment would not be possible without your constant guidance, and the sacrifices that you have made for years in order to make me succeed and become a better person. I would not be more than grateful to have you as my parents. Also, to my brother that is being there every moment of my life and that without your continuous challenges I could not be able to put all my effort and dedication to set path for you. This is another challenge that I am setting up for you and that you will need to overcome it and be better than I was. My girlfriend Alejandra, you have been an amazing person and your constant support made me to keep going when things where not to clear for me and even when I was close to quit. My uncle Efren and the rest of my family, this would never be possible without your help and support. Being at UTEP was a dream that I was able to follow and achieved thanks to the financial support, but more than that to the trust, affection, and love that you have always provided to me. Lastly, but not less important, to all my friends that have been there for me through my career, classes, work and more where you all made me to keep going and succeed.

# EFFECT OF TEMPERATURE ON A PIEZOELECTRIC MASS FLOW RATE SENSOR SIGNAL

by

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**Abstract**

On this research, we are trying to demonstrate that a piezoelectric flow sensor made of PZT can produce a higher and fluctuating signal when exposed to elevated temperatures presented on the system. This type of application can be beneficial for systems that involve changes in temperature such as compressors and be able to predict certain situations presented on those systems that can be catastrophic, that is the case for surge and stall. Therefore, a system capable of going from 25ºC-90ºC was designed where a piezoelectric sensor was inserted at a specific location to analyze the signal produced by these changes in temperature. For this investigation, the mass flow rate in the system was kept the same, 0.07kg/s, and the only variable was the temperature. Compared to the previous phase, it was observed that at a lower velocity and same mass flow rate, the output signal of the sensor was higher when a higher temperature in involved. From this, we concluded that the signal of a PZT flow sensor is affected by the changes in temperature and it follows the trend of the temperature. Therefore, if the temperature increases, the signal from the sensor increases and this will be occurring until the curie temperature is reached. However, if this investigation wants to be used for applications where the temperatures are higher that the curie temperature of the PZT (around 250ºC), then, different sensor materials capable of handling the specified temperature will have to be studied and analyzed to see how they behave under those circumstances.

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# Chapter 1: Background & Introduction

## 1.1 INTRODUCTION

### 1.1.1 Piezoelectric

The word “piezoelectric” is derived from the Greek word “piezein”, which means to squeeze or press, and “piezo” is Greek that means push. There is an effect caused by these sensors that is called “Piezoelectricity” in which, certain crystalline materials can develop electrical charge proportional to a mechanical stress and vice versa [1,2]. When a mechanical load is applied, the piezoelectric produces a direct effect where the displacement cause by the stress applied can be translated to a voltage by using some of the properties of the sensor. On the other hand, when an electrical load is applied to the piezo, this produces a converse piezoelectric effect where a mechanical strain is the output value, then it is translated to displacement and from this, a stress can be obtained.  This relationship can be represented by the Eq. (1).

$$\begin{bmatrix} \epsilon \\ D \end{bmatrix} = \begin{bmatrix} s & d \\ d & k \end{bmatrix} \begin{bmatrix} \sigma \\ E \end{bmatrix} \qquad \text{Eq. (1)}$$

Mechanical strain (ε), compliance matrix (s), piezoelectric coupling coefficient (d), dielectric displacement (D), mechanical stress (σ), electric field (E), dielectric constants matrix (k). These variables represent the properties that are needed to produce a direct or converse effect in a piezoelectric material [2,3,4].

### 1.1.2 Piezoelectric Applications

Applications where piezoelectric crystal materials are being used have been increasing throughout the years. One of the reasons of this is due to his high durability and low cost compared to other available devices on the market that produce similar results. Piezoelectric devices have been researched in different areas such as wind, solar, ocean, tidal, full cells, rain, geothermal, biofuels, and hybrid systems, where the main advantage of these devices compared to conventional sources in those previously mentioned areas is to harvest the energy [5, 6]. A clear example of this, is the research conducted by Weinstein et al [6] where a piezoelectric material is utilized as a cantilever beam in heating, ventilation, and air conditioning flows. Sirohi and Mahadik [7] presented a way to harvest wind energy by using a galloping piezoelectric beam. The main purpose of their device is to power wireless sensors that are used in health monitoring of civil structures.

### 1.1.3 Piezoelectric Properties and Materials

There are different applications where piezoelectric materials have been used, but each application requires a specific material characteristic that fit the necessities of the application. One of the most common materials for piezoelectric is Lead Zirconate Titanate (PZT) because is it commercially available and can be utilized for many applications. However, there are other applications where high temperature is involved, for high temperature applications the performance of the piezoelectric material depends on the Curie temperature (Tc). This is mostly because most piezoelectric sensors have a Tc of 300ºC - 700ºC. Piezoelectric materials above this temperature range become less sensitive, mechanical properties are affected, depolarization and piezoelectricity can be lost, and overall less durability have been observed [8,9,10]. The following table represents the most common piezoelectric crystals for high temperature applications that are currently commercially available

*Table 1. High Temperature Materials Commercially Available* [8]

| Material | Structure | $T_c/T_{melt}$(℃) | $\varepsilon_\Gamma$ | $d_{33}$(pC/N) |
|---|---|---|---|---|
| Ferroelectric ceramics | Single crystals | | | |
| • $BaTiO_3$ | Perovskite | 115 | 1700 | 190 |
| • $PZT-5A$ | Perovskite | 330 | 2000 | 400 |
| • $PbTiO_3$ (modified) | Perovskite | 470 | 200 | 60 |
| • $PbNb_2O_6$ (modified) | Tungsten bronze | 500 | 300 | 85 |
| • $Bi_4Ti_3O_{12}$ | Aurivillius | 675 | 180 | 20 |
| • $CaBi_4Ti_4O_{12}$ | Aurivillius | 800 | 150 | 14 |

| | | | | |
|---|---|---|---|---|
| • $La_2Ti_2O_7$ | Perovskite layer | 1460 | 60 | 2.6 |
| • $LiTaO_3$ $(crystal)$ | 3 m | 720 | 43 | 6 |
| • $LiNbO_3$ $(crystal)$ | 3 m | 1150 | 28 | 6 |
| Piezoelectric | Single crystal | | | |
| • $\alpha - Quartz$ | 32 | 570 | 4.5 | ~3 |
| • $Tourmaline$ | 3 m | 1100-1200 | 6 | ~2 |
| • $GaPO_4$ | 32 | 1650 | 6-7 | 4-5 |
| • $Langasite$ $(La_3Ga_5SiO_{14})$ | 32 | ~1470 | 16-20 | 4-7 |
| • $Oxyborate\ ReCOB$ | m | ~1500 | 11-12 | 5-7 |

Piezoelectric materials have different crystal structures. These structures or families are characterized to affect the materials in different manners. The family of ferroelectric material structures includes structures that can handle higher temperatures without affecting their properties compared to those in the non-ferric material structures. Therefore, in the non-ferric family, the structures suffer on the phase transition temperatures, oxidation, and other aspects that lead them to only handle low temperatures to not be affected by the mentioned side effects [8]. The following tables, show the properties of some materials offered by the ferroelectric family with different structures, Perovskite, Aurivillius and PLS.

*Table 2. Properties of Different PZT Types* [10]

| **Materials** | $T_c$ (°C) | $\varepsilon_{33}^T/\varepsilon_0$ | $d_{33}$**(pC/N)** | $d_{15}$**(pC/N)** | $k_{33}$ **(%)** | $k_{15}$ **(%)** |
|---|---|---|---|---|---|---|
| • $BaTiO_3^{25}$ | 115 | 1700 | 190 | 260 | 50 | 48 |
| • $Pb\left(Mg_{\frac{1}{3}}Nb_{\frac{2}{3}}\right)O_3 - PbTiO_3^{35}$ | 160 | 6900 | 800 | 1090 | 78 | 71 |
| • $PZT5H^{25}$ | 193 | 3400 | 600 | 740 | 75 | 68 |
| • $PZT5A^{25}$ | 365 | 1700 | 370 | 580 | 71 | 69 |
| • $Pb(Yb_{.5}Nb_{.5})O_3 - PbTiO_3^{36-37}$ | 370 | 2800 | 510 | 710 | 75 | 72 |
| • $BiScO_3 - PbTiO_3 - Mn^{38}$ | 442 | 1450 | 360 | 520 | 69 | 67 |
| • $BiInO_3 - PbTiO_3^{40}$ | 542 | 250 | 60 | 85 | 40 | 38 |
| • $PbTiO_3^{25}$ | 470 | 190 | 56 | ---- | ---- | ---- |

*Table 3. Properties of Different PZT Types* [10]

| Materials | $T_c$ (°C) | $\varepsilon_{33}^{T}/\varepsilon_0$ | $d_{33}$(pC/N) | $Q_M$ | $k_p$(%) | $k_t$(%) |
|---|---|---|---|---|---|---|
| • $CaBi_4Ti_4O_{15}$ $(textured)$ [62] | - | 139 | 45 | 4000 | 4.8 | 53.4 |
| • $CaBi_4Ti_4O_{15} - Na, Ce$ [58] | - | 140 | 20 | - | - | - |
| • $CaBi_4Ti_4O_{15} - Mn$ [67] | 800 | 148 | 14 | 4300 | - | - |
| • $CaBi_2Nb_2O_9$ $(textured)$ [60] | 943 | - | 19 | - | - | - |
| • $(SrBi_2Nb_2O_9)_{.35}(Bi_3TiNbO_9)_{.65}$ [63] | 760 | - | 20 | - | 7.4 | - |
| • $Bi_3TiNbO_9 - W$ [59] | 909 | - | 12 | - | - | - |
| • $Bi_4Ti_3O_{12} - Nb$ [44] | 655 | 196 | 20 | - | - | - |
| • $0.9Na_{.5}Bi_{2.5}Nb_2O_9 - .1LiNbO_3$ [66] | 789 | 192 | 21 | 2700 | 12.8 | 24.5 |
| • $(Na_{.84}K_{.16}Bi)_{.38}(LiCe)_{.05}Bi_4Ti_4O_{15}$ [52-53] | 660 | 180 | 25 | 3100 | - | - |
| • $(K_{.5}Bi_{4.5}Ti_4O_{15}) + 0.5wt\%\ CeO_2$ [54] | 550 | 245 | 28 | 2800 | 4.3 | 15 |
| • $(Na_{.5}Bi_{4.5}Ti_4O_{15}) + 0.3wt\%\ CoO$ [55] | 663 | 152 | 30 | 3800 | 5.0 | 34.2 |
| • $Ca_{.9}(NaCe)_{.05}Bi_2Nb_2O_9$ [56-57] | 900 | 85 | 16 | 8200 | 8.8 | 22.3 |
| • $Sr_2(Nb_{.5}Ta_{.5})_2O_7 - La$ $(Perovski\ Layer\ Structure)$ | 840 | 60 | ~2 | - | - | - |
| • $La_2Ti_2O_7(textured)$ $(Perovski\ Layer\ Structure)$ | 1461 | 46 | 2.6 | - | - | - |

## 1.2 BACKGROUND

There has been significant research done on piezoelectric materials used as a sensor in high temperature applications. Krishnamurthy, Lalande, Rogers (1996), used a piezoelectric sensor and found out that the dielectric constant and the piezoelectric coefficient are influenced by the temperature applied. The effect of temperature on a free piezoelectric sensor and a bounded sensor was shown to be different. A temperature coefficient independent from the frequency was established to describe the effect of temperature on the electrical impedance and based on this coefficient a compensation technique was created to eliminate the effects of temperature of the PZT sensor only [11].

In a changing temperature setting, piezoelectric devices react to the temperature variatios. H.S Tzou and R. Ye (1996), analyzed this effect and demonstrated that temperature-induced generation of piezoelectric sensors can be divided into 2 major components: the pyroelectric effect which is a direct temperature effect, and the thermal strain effect which is an indirect temperature effect as the voltage generation is caused by the thermally induced strain imposed by the difference in temperature. In the analysis it is observed that the pyroelectric effect is insignificant on the PZT. However, the thermal strain effect is significant [12].

Piezoelectric sensors have been studied in recent years for the use in Structural Health Monitoring method (SHM). Baptista, Budoya, Almeida, and Ulson (2014), showed that the change in temperature causes variations in the electrical impedance of a PZT in SHM. The experimental results suggested that the variations in the amplitude of the impedance signatures were related to the temperature-dependence of the piezoelectric sensor capacitance. Furthermore, the frequency changes of the resonance peaks resulting from fluctuations in temperature were not constant over the entire frequency range but increased with the frequency. Temperature effect are therefore a critical problem for structural health monitoring based on electromechanical impedance, particularly in detecting low levels of damage, and it remains to develop effective compensatory methods for temperature effects [13].

Temperature has a profound effect on the properties of piezoelectric. Birman (1966), showed that temperature affects the voltage in piezoelectric sensors via three mechanisms: 1) influence on the properties of the piezoelectric and composite substrate materials, 2) thermal forces and 3) moments in the structure. The latter effect is prominent if the substrate is manufactured from a polymeric composite material, because polymeric matrices are more affected by temperature than metallic or ceramic materials. It is shown that even moderate fluctuations of temperature can significantly change the voltage reading from a piezoelectric sensor. It was concluded that the effect of temperature on voltage depends on the material of the piezoelectric, and on the properties, lay-up, and geometry of a substrate [14].

Ultrasound transducers are used in various applications, where an ultrasound transducer consists of a piezoelectric layer, one or more matching layers and a backing layer, where the most used piezoelectric is a Lead zirconate titanate (PZT). The resonant frequency of a piezoelectric element can be affected by the change in temperature and pressure. Upadhye and Agashe (2016), test this effects on a PZT with a varying temperature from 5℃ to 50℃ where it was shown that when the temperature increase the resonant frequency of the PZT decrease and it is directly proportional to the stiffness that decrease as the temperature increase; and when pressure is increasing the resonant frequency is increasing too [15].

Krishnamurthy, Lalande and Rogers (1996), used a piezoelectric sensor and find out that the dielectric constant and the piezoelectric coefficient are influenced by the temperature applied. The effect of temperature on a free piezoelectric sensor and a bounded one was shown to be different. A temperature coefficient independent form the frequency was established to describe the effect of temperature on the electrical impedance and based on this coefficient a compensation technique was created to eliminate the effects of temperature of the PZT sensor only [16].

Kabeya (1998), found that the temperature changes significantly influenced both on the PZT sensor-actuators and the structure being monitored, where the temperature change causes vertical and horizontal shifts of the signature pattern in the impedance versus frequency plot. The impedance variation associated with temperature change is like that produced by the presence of damage. Kabeya developed an empirical temperature compensation technique to remove the temperature effects from the Structural Health Monitoring, with this technique the effects of temperature where minimized giving a more accurate results on the impedance-based structural health monitoring technique that now was able to detect incipient type damage such as loosening a bolt by 1/6 turn even with temperature variations [17].

Perez (2020), worked on previous phase of the research that involves the study of a piezoelectric sensor that has been used to analyze how the signal (voltage) is affected at room temperature by changing the mass flow rate coming into the system and hitting the sensor. This was done by creating a system where the velocity of a fan was controlled at different percentages and then the fluid, that in this case was air, hit the piezoelectric sensor located at the center of the system. Here, it was observed that the signal was higher as the velocity was increasing [18].

### 1.3 Objective

There have been multiple researchers studying piezoelectric sensors and how temperature impacts the amount of voltage produced by the material. Previous investigations found in literature have been found to include studies on vibrations and how piezoelectric properties get affected during conducted tests at high temperatures. In this study, the piezoelectric material will be implemented on system where air is the fluid and then this is heated to different temperatures below the Tc of the material. The objective of this research is to quantify the signal (voltage) of a piezoelectric sensor at elevated fluid temperatures and compare with results at room temperature.

To do this, theory and experiments are used to compare the different values from elevated and room temperature results. These results will contribute to the development of a piezoelectric mass flow rate sensor explained by Perez [18]. Thus, to successfully develop the experimentations and compare the multiple results, the following tasks must be undertaken:

Task 1: Design the elevated temperature experimental setup.

Task 2: Measure the effects of velocity on the piezoelectric signal at room temperature

Task 3: Measure the effects of temperature on the piezoelectric signal at the same velocity

Task 4: Compare experimental results with existing models

### 1.4 Practical Relevance

Surge and stall in the systems is a problem for compressors since it is hard to predict. This occurs when the fluid detaches from the blades at an angle that causes the boundary layer to be affected. Therefore, when the system faces these anomalies, it could result in catastrophic failure of the compressor.

One example of this can be seen in the Hybrid Facility Performance (HYPER) experimental loop located at the National Energy and Technology Laboratory (NETL). The piezoelectric sensor can be implemented into this facility after the compressor in order to measure discrepancies in the signal of the fluid and if a discrepancy in the signal occurs, the system can be shut down to prevent any damage.

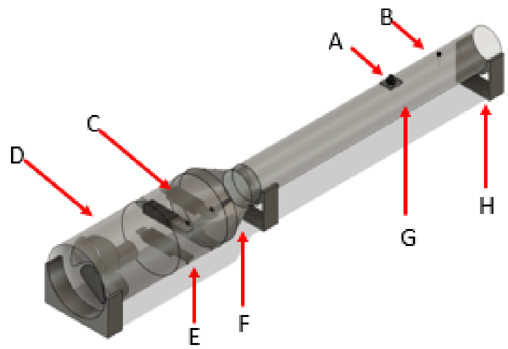
# Chapter 2: Methodology

## 2.1 EXPERIMENTAL DESIGN PROCESS

A setup is designed that delivers a high temperature fluid to a piezoelectric sensor to determine the effect of velocity and temperature and compare them with results at room temperature.

### 2.1.1 High Temperature Test Section (HTTS) Setup

*Figure 1* represents the different components of the High Temperature Test Section (HTTS). A fan is used to generate the air mass flow for the system where the speed of this fan is controlled. Air flows to the system and when it reaches the heaters, the air is heated up at different temperatures depending on the number of heaters that are activated. The heated




| A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|
| Piezo/Mounting | Thermocouple | Heaters | Ventilation Fan | 12'' Extension Pipe | Reduction | 6'' Pipe | Supports Pipe |

*Figure 1 HTTS Setup and Components*

air enters a reduction that is followed by a long extension where the sensor is located. The piezoelectric sensor is attached to a mount close to the exit of the duct. The interaction between the sensor and fluid leads to the piezoelectric vibration and generation of voltage for each condition. To record the voltage and temperature of the sensor and fluid respectively, a DAQ system was utilized and the LabView NXG software was used to get these readings at a specific sample rate, *Figure 2*.

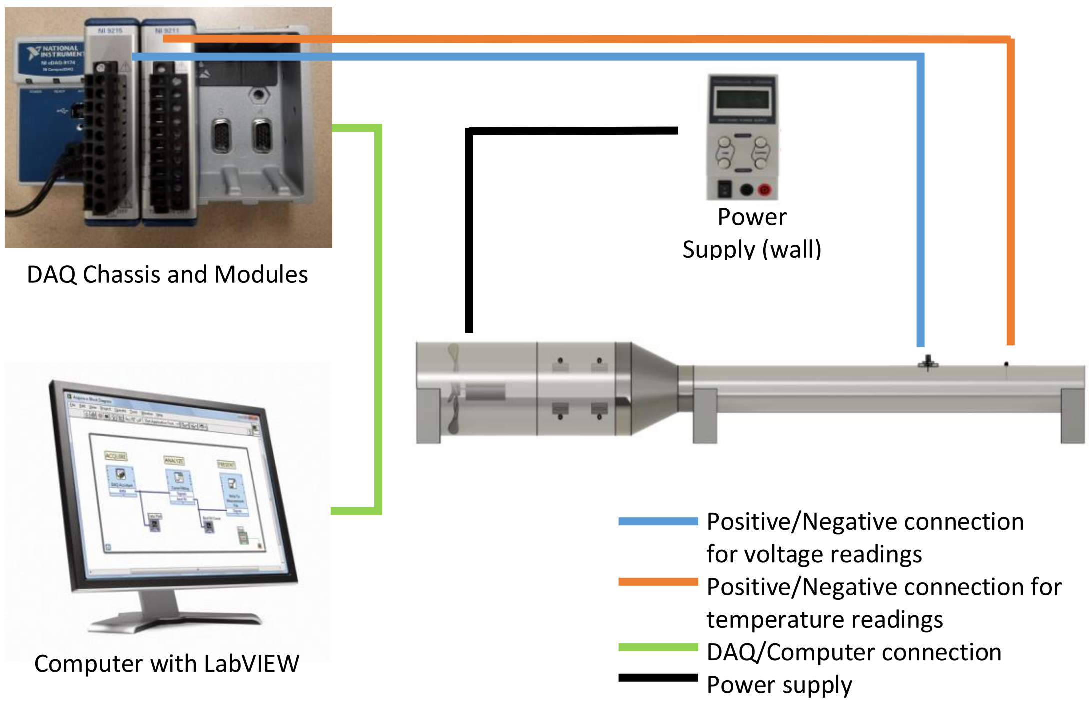
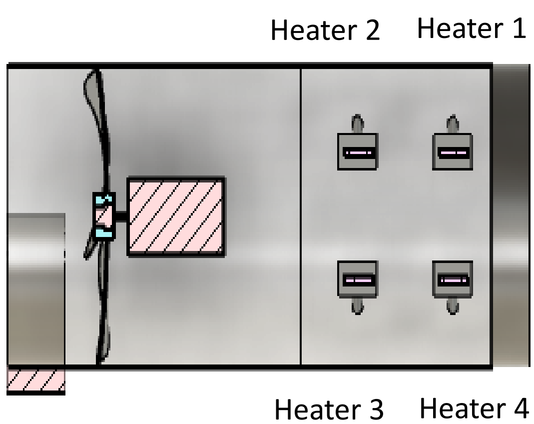



*Figure 2 HTTS layout and control schematic*

The HTTS consists of a 12-inch diameter fan that works as the inlet of the system and a controller is used for the fan to be able to adjust the power. The mass flow rate can be adjusted to 2 different settings, low and high. Then, this fan is attached to a 12-in galvanized steel with a length of 10 inches that works as an extension. In this extension, 4 heaters a horizontally located where two of those heaters are on top and two on the bottom. The heaters have the dimensions of 10 x 2 x 2. These heaters are attached to the extension by metal screws, also, they are wired with a thermal cable that can resist up to 300 ºC and then wired to a power cord. This is mainly done to prevent the plastic of the power cord to melt inside the system. At the end of the extension, there is a metal reduction that goes from 12 to 6 inches. After the reduction, a 6 in galvanized steel pipe with a length of 60 in is attached to this. In this pipe, 2 flow straighteners are located before the flow reaches the sensor. The mount and the piezoelectric sensor are located 30 inches after the reduction and a thermocouple is inserted 10 inches after the sensor to take the reading of the temperature at the same time as the piezoelectric signal. The mount of the sensor is made of high temperature resin. Finally, two bases hold the galvanized pipe to level it, these are made of polylactide (PLA). *Figure 3* shows the configuration of heaters in the duct.

*Figure 3 Heaters Labels*




This figure represents the order on how the heaters were set and labeled for the HTTS. Also, this helped to see what heater was going to be turned on and to always keep the same procedure for all the experiments.

### 2.1.2 Piezoelectric Mount and Support Base

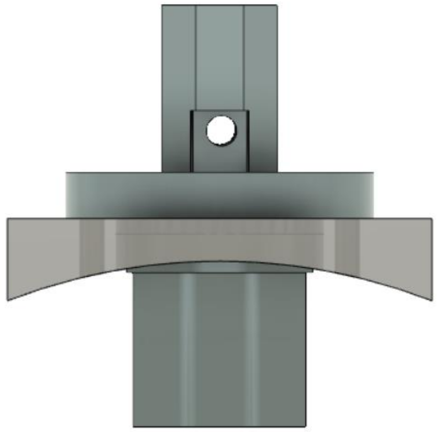


*Figure 4 Mount and Support for Sensor*

The mount for the piezoelectric sensor and the support base are made of high temperature resin from Formlabs using the stereolithography additive manufacturing method. This resin offers a high deflection temperature (HDT) of 238ºC at 0.45MPa where the elongation is improved to decrease the brittleness of the material. High temperature resin is good for product development, testing and validation and production processes. Some of the applications are kitchen appliances

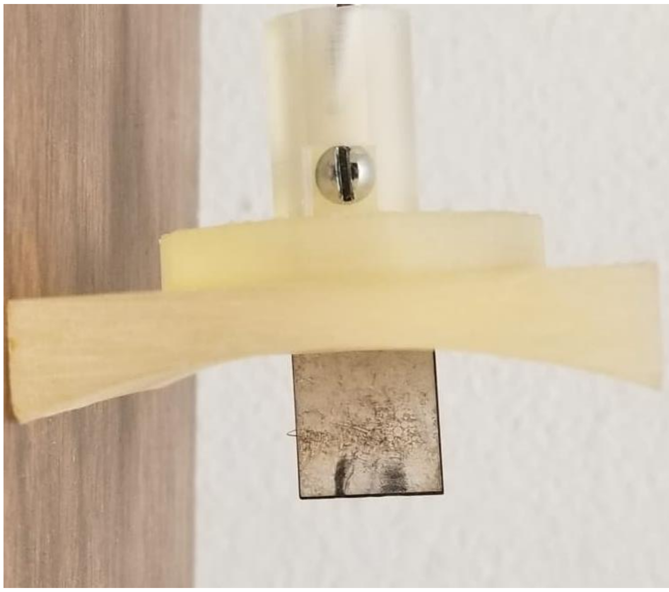


*Figure 5 Actual Piezoelectric Sensor and Base Support*

mount sensors for wind tunnel testing, create molds for parts and more. Material was used over other additive manufacturing materials since the study involves high temperature and the heat transfer could be higher than the actual testing temperature. Therefore, if other material was selected such as PLA where it has a glass transition temperature ($T_g$) between 60-65ºC, the material could melt and damage the sensor or affect the accuracy on the experiments. *Figure 5* is an actual representation of how the piezoelectric sensor looks once attached to the mount and

## 2.2 LIST OF INSTRUMENTATION

### 2.2.1 Portable Ventilation Fan and Controller

*Figure 6 Ventilation Fan retrieved from https://www.deelat.com/*

The fan is used to provide mass flow of air to the system. Ducts are connected to the 2 sides of the fan. It has a single-phase motor that rotates only on one direction, flow rate cannot be adjusted unless a device is attached to the power cord. For this study, the fan is set to circulate air (inlet) and the other end is connected to an extension (outlet). The fan model number is D1143670, it has a nominal voltage of 110V, a power of 520W, a maximum revolution per minute (RPM) of 3300 and produced a volume flow rate of 65m^3/min.

Also, for this study, a BN-LINK exhaust variable speed fan (controller) is used to reduce


*Figure 7 BN-LINK Fan Controller*

the mass flow rate that the fan produces. It has a max voltage of 125V, 600W or 4.8A. It is a small block with dimensions of 2.125 x 2.0 x 3.625 inch. The male part of the power cord of the fan is connected to the femal part of the controller. The controller has a small knob that can be adjusted to the desire setting.

#### 2.2.2 Heaters

*Figure 8 Heaters*

A finned strip heater works as a fast heat transfer device in a system to increase or decrease the temperature in a short period of time. The model of the heaters that were used on this study is OTF-106/120 from Omega Engineering. The heaters are made of rust-resisting iron with a length of 10 ½ inch, a strip width of 1 ½ inch and the finned section has a width of 2 inch. They need a power of 600W and 120V where the power density is 38.75kW/m^2 and can reach a temperature of 400ºC. The maximum temperature is reached at atmospheric conditions. Also, the heater has two holes, one at each end, and two terminals on a single side.

### 2.2.3 Hotwire Anemometer


*Figure 9 HWA2005DL Hot Wire Anemometer with Real-Time Data Logger*

The anemometer from *Figure 9* is used in this study because it measures velocity and temperature at a point. This device is able to connect to a thermocouple of type J or K that can be used. Based on the temperature measured, the resistance of the wire on the tip of the anemometer starts to adjust the velocity and it results in a more accurate value for the velocity.

### 2.2.4 Data Acquisition System


*Figure 10 NI Compact DAQ Chassis (cDAQ-9174)*

The National Instruments Compact Data Acquisition hardware model NI cDAQ-9174 is a 32-bit USB chassis that can port up to 4 different modules. This chassis is connected via USB to the computer from that respective port and the other is for the power source. It is capable of controlling time, synchronization and transfer data between C Series I/O modules and an external host. The modules can be mixed if they can be attached to this chassis. This device was used to hold two different modules (temperature and voltage) and transfer the data to the LabView NGX software and record it for the experiments.

### 2.2.4.1 Temperature Module


*Figure 11 Temperature Module NI-9211*

For this study, the C Series Temperature Input Module NI-9211 from NI is used to record the temperature in the system. This module has 4 channels and a 14 Sample/s aggregate. It has anti-aliasing filters, open-thermocouple detection, and cold-junction compensation for high accuracy thermocouple measurements. In the study, only one channel is occupied by the thermocouple that is located after the sensor. More thermocouples can be added on the other channels if necessary.

### 2.2.4.2 Voltage Module


*Figure 12 Voltage Module NI-9215*

The 16-bit C Series Voltage Input Module NI-9215 is used to take the reading of the voltage that the piezoelectric sensor is producing. This module is also a 4 channel that can read 10 volts in both directions, positive and negative, has a 100,000 Sample/s/ch and a simultaneous input. It has NIST-traceable calibration, a channel to earth ground double isolation barrier for safety, a noise immunity, and high common mode voltage range. On this device, the sensor is connected to one of the channels as the temperature module, the data is transferred to LabView NXG to record the data.

### 2.2.5 Thermocouple

*Figure 13 Thermocouple M12KIN-1/8-U-1.3-D*

A thermocouple model M12KIN-1/8-U-1.3-D from Omega Engineering is used in this study to record the temperature in the system. This is a probe thermocouple type K made of Inconel 600 Sheath and can resist temperatures that go from 0-1070ºC. The probe is a 1/8inch diameter and a 2inch length. A cable is attached to the end of the thermocouple and then connected to the temperature module.

### 2.2.6 Piezoelectric Sensor Properties

There piezoelectric material used in this study is Lead Zirconate Titanite (PZT). This is a relatively hard sensor with the characteristics listed in *Table 4.*

*Table 4. Piezoelectric Characteristics*

| **Material Characteristic** | **Piezoelectric Sensor (PZT)** |
|---|---|
| Piezoelectric Constant | Small |
| Permittivity | Low |
| Electromechanical Coupling Factors | Small |
| Electrical Resistance | Low |
| Dielectric Constant | Small |
| Dielectric Losses | Low |
| Coercive Field | High |
| Mechanical Quality Factors | High |
| Polarization / Depolarization | Difficult |
| Linearity | Good |

The piezoelectric sensor used for this study has a rectangular shape with dimensions of 0.79 x 0.59 x 0.04 inches, *Figure 14.* The composite material is blend of ceramic with an epoxy or polymer that helps to reduce the acoustical impedance and that results in a higher coupling

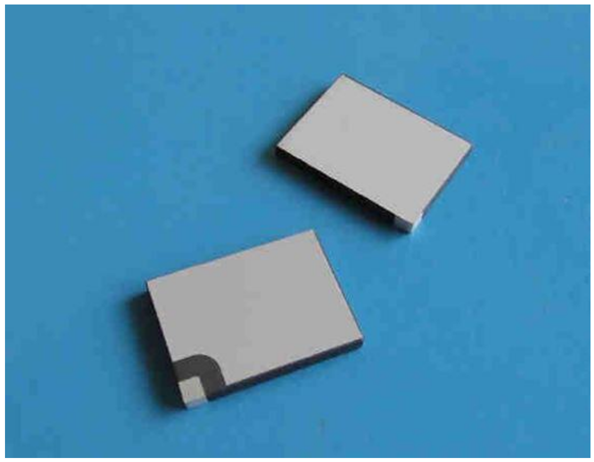


*Figure 14 Piezo with dimensions 2 x 1.5 x 0.1cm, retrieved from* https://www.steminc.com

coefficient. *Table 5* shows the properties of the piezoelectric sensor that is used in the study. This sensor required a couple of cables attached via two silver electrodes on both sides of the sensor to measure the voltage output. Then the cables were checked and then connected to the voltage module. In this study, the sensor is used to investigate the relationship of the flow at different temperatures and the voltage signal that is obtained from the sensor.

### 2.2.7 Piezoelectric Material Properties

*Table 5* represents the properties of the piezoelectric sensor that was utilized in this study.

*Table 5 Piezoelectric Sensor Material Properties*

| Properties | Symbol | Value | Units |
|---|---|---|---|
| **Frequency Constant** | $N_p$ | 2200 | $Hz.m$ |
| | $N_t$ | 2070 | |
| **Coupling Coefficient** | $K_t$ | 0.45 | – |

| | | | |
|---|---|---|---|
| | $K_{31}$ | 0.34 | |
| **Piezoelectric Constant** | $N_{31}$ | 1680 | $\times 10^{-12} \mathrm{m/v}$ |
| | $d_{33}$ | 320 | |
| | $d_{31}$ | -140 | |
| **Curie Temperature** | $T_c$ | 320 | $C^o$ |
| **Density** | $\rho$ | 7.9 | $\mathrm{g/cm^3}$ |
| **Dielectric Constant** | $\varepsilon_{33}^{T}/\varepsilon_0$ | 1400 | @ 1 kHz |

For the PZT sensor, the $T_c$ temperature is 320ºC at this temperature the sensor gets depolarized. However, this study works with a range in temperatures from 23ºC to ~90ºC. Thus, the piezoelectric material properties should not be compromised for the current project.

### 2.3 EXPERIMENTAL SETUP

For this study, there are some initial conditions that were used for the calculations. These values are shown in *Table 6.* Also, the maximum power was set to be the one proportionated by the circuits from the walls in the lab.

*Table 6 Initial Conditions*

| Symbol | Variable | Value | Units |
|---|---|---|---|
| $T_1$ | Initial temperature | 22 | ℃ |
| $P$ | Pressure | 101.325 | $kPa$ |
| $\rho$ | Density at room temperature and pressure | 1.2 | $\frac{kg}{m^3}$ |
| $C_p$ | Specific heat | 1 | $\frac{kW}{kgK}$ |

| | | | |
|---|---|---|---|
| $T_2$ | Final temperature | ~90 | ℃ |

After setting these conditions, the next condition was to set the fan to the desired setting, in this case, it was set to be low. Once the fan was, the heaters were turned on to see the time that they would take to reach steady state and the time to cool down. Then, the temperature that each heater would reach under the given mass flow rate by the fan was measured to compare the results with the hand calculations. Finally, before inserting the sensor, the velocity profile was measured with both flow straighteners at their respective locations. For this measurement, the hot wire was inserted where the sensor will be inserted.

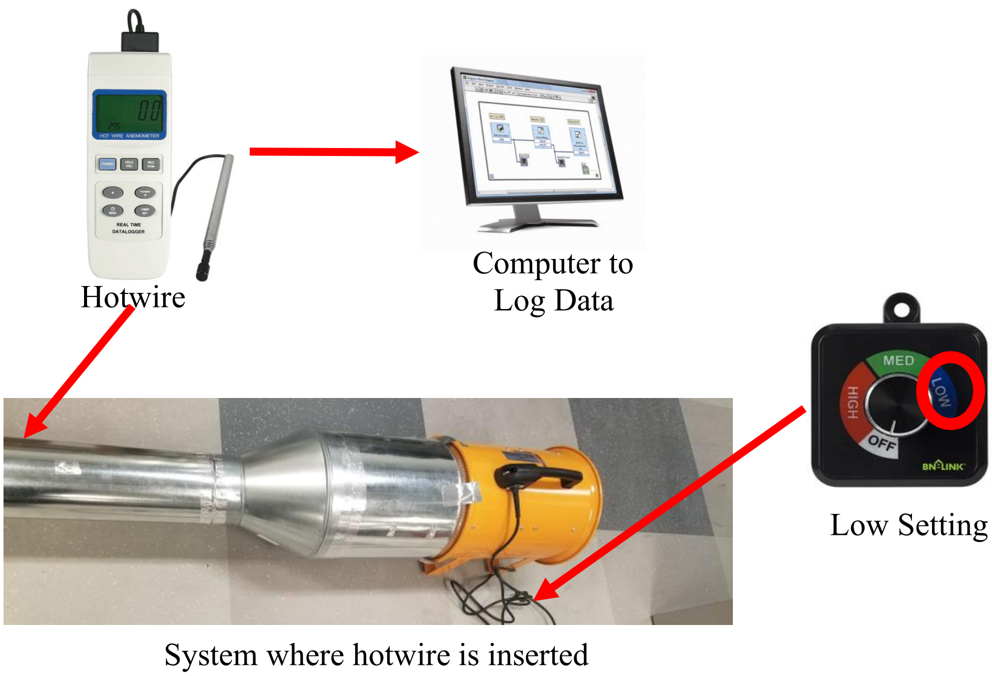



*Figure 15 Low Setting Diagram*

Then, velocity for points at different distances were measured and averaged. *Figure 15* is a diagram of the setup at low setting when the hotwire is attached to it to measure the velocity profile. Then, the maximum temperature of the heaters was measured to see what the temperature conditions would be when 1 to 4 heaters are turned on.

# Chapter 3: Results and Discussion

## 3.1. EFFECT OF TEMPERATURE ON PIEZOELECTRIC SENSOR SIGNAL

### 3.1.1 Calibration

For this research, some calibration was conducted to obtain the most reliable data from each experiment. As mentioned before, two flow straighteners were inserted in the reduction pipe and separated one from the other. This was done with the finality of obtaining a velocity profile that could be suitable to start conducting the experimentation of the piezoelectric sensor. At the beginning only one flow straightener was inserted, but since the piezoelectric was 0.5m apart from the flow straightener, the flow was having some disturbances when reaching the location of the sensor. This was causing a fluctuation on the signal. Therefore, a second flow straightener was inserted closer to the sensor location, but with a distance that was considered enough to fully develop the flow in the system. After this, the velocity profile at the sensor was recorded to be almost the same over several tests with only small variations in all the vertical distances recorded. The points were measured starting at 0.01m from the bottom of the pipe since that is where the actual sensor of the hot wire and raised up 0.025m to have a total of 6 distances in the pipe and reaching the top of 0.14m. *Figure 16* shows the velocity profile recorded at the different distances of the sensor once the two flow straighteners were inserted in the testing system.

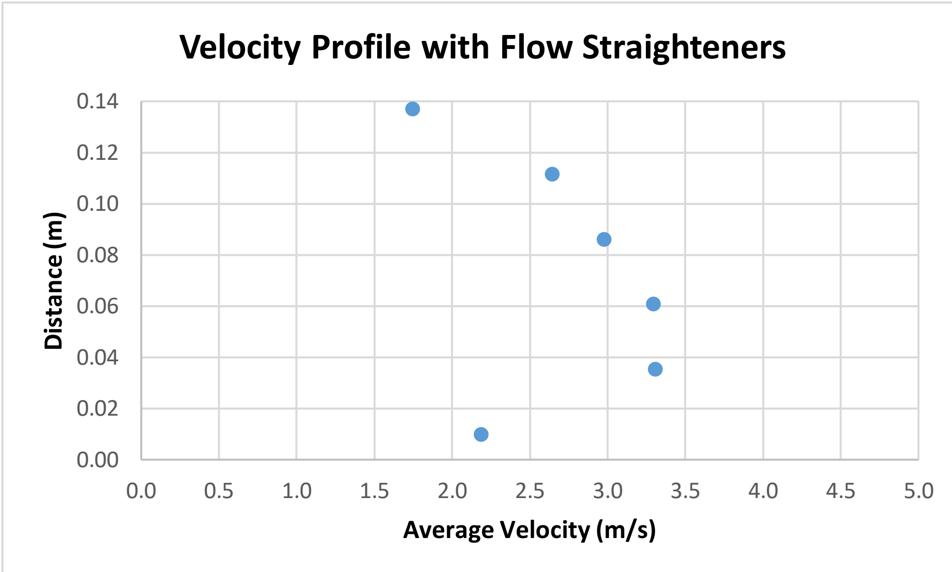



*Figure 16 Velocity Profile with Flow Straighteners*

From the velocity profile, it can be appreciated that the point that is closest to the wall (0.01m) is the only point that does not follow a trend and is far in terms of velocity from the other recorded values. That is because the velocity at the walls is zero due to the no slip condition. From the multiple tests conducted for the velocity profile, a mass flow rate of 0.07kg/s was calculated from the maximum velocity recorded in the system with a margin of error of 0.007 and a standard deviation of 0.003 between the tests. After calibrating the flow in the system, the next calibration performed was for the heaters. The finality of this was to know the time that a heater was going to take to reach the maximum temperature and to reach a near room temperature. For this, a thermocouple was used to record the temperature and time.

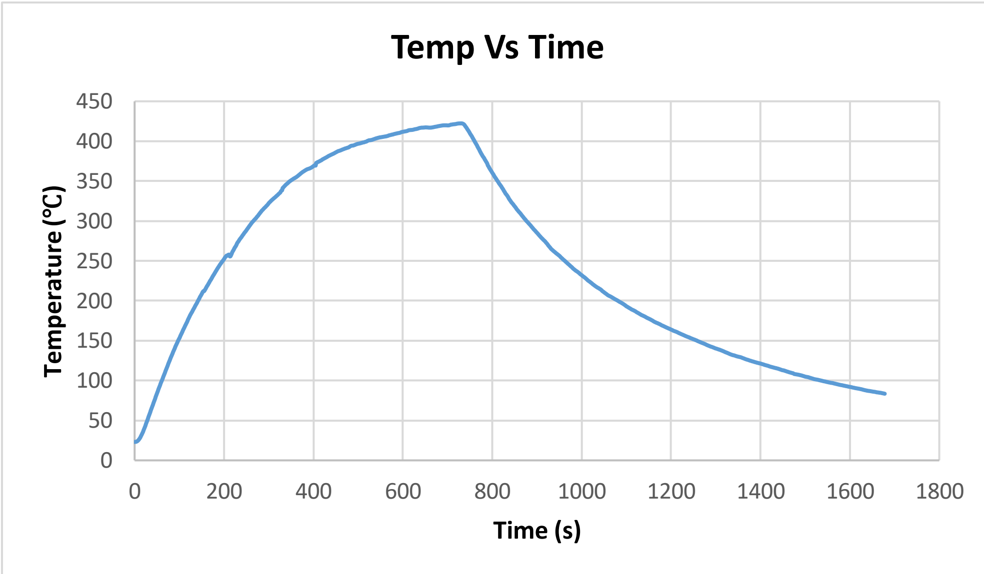
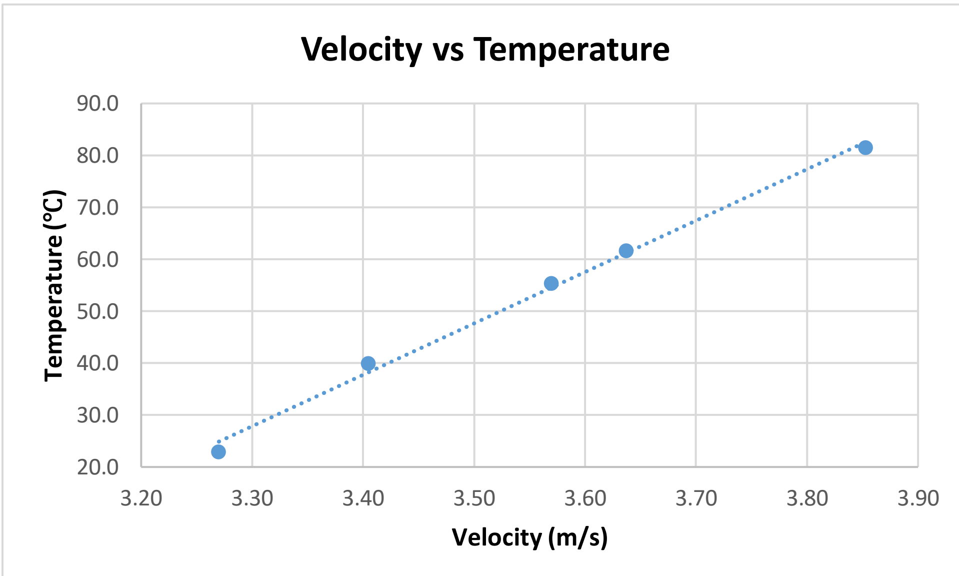



*Figure 17 Time to reach maximum temperature and near room temperature*

*Figure 17* represents the heating and cooling times for the heaters. Here, it can be appreciated that the heaters take around 750 seconds that is 12.5 minutes to reach the maximum temperature and almost 950 seconds that is the equivalent to ~16 minutes to reach room temperature. The temperatures recorded are far from the obtained ones in the conducted experiments with the sensor since a higher mass flows in the systems and the heat transfer needed to heat up that amount of mass in higher. Since some experiments with the piezoelectric sensor were conducted almost one after the other, to reduce the cooling time, the fan was set to 100% to achieve the needed temperature in a shorter amount of time and conduct as many experiments as possible in a single day to keep the same conditions. Therefore, after putting the heaters in the system and start conducting experiments, the heaters were left running for 15 minutes with the fan on to reach the maximum temperature. The extra 2.5 minutes from the recorded time were only to assure a steady state condition and have the collected date as accurate as possible. Lastly, the velocity was corrected with the change in temperature. To do this, 4 different temperature were taken from the experiments and the velocity at each scenario was calculated and the density was also considered for each temperature. The fixed values for the calculations was the area and the mass flow rate since those are constant values. *Figure 18* represents the maximum velocity in the system at the given temperature.

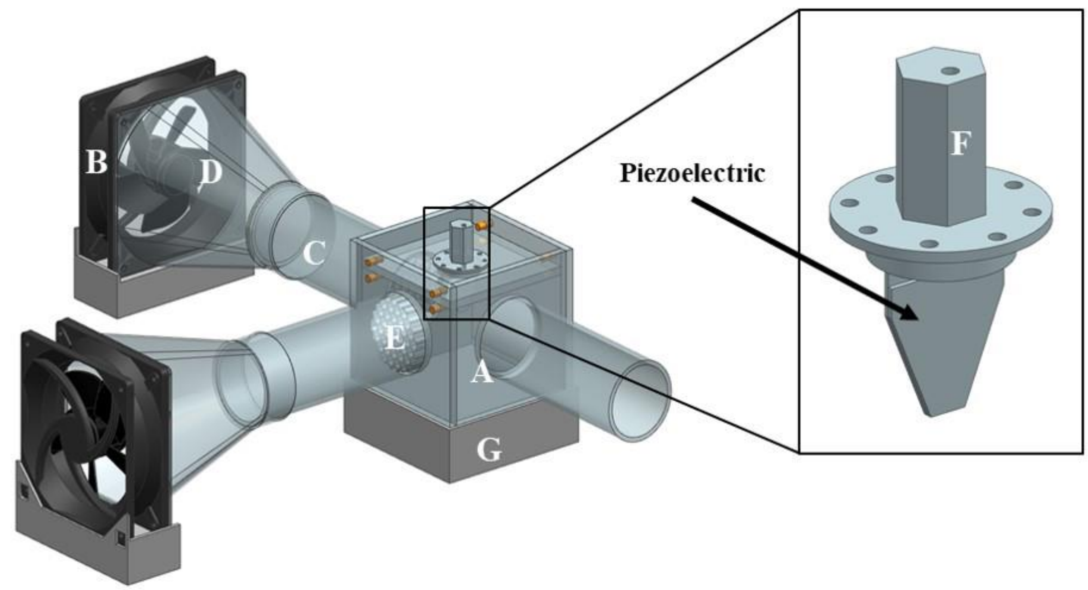
*Figure 18 Velocity and Temperature Relationship*




On the graph, the velocity is observed to be almost linear and a difference of 0.58m/s between the temperatures at 23℃ and 81.5 ℃. That is close to 0.01m/s every time that temperature is increased by 1℃. That shows that when temperature increases, the velocity remains almost constant with small variations on it.

### 3.1.2 Signal at Room Temperature (Phase I) vs High Temperature (Phase II)

This section shows the comparison of the results from the previous phase done by Perez with this second phase. Both phases involve the use of the same piezoelectric sensor at different test conditions, room temperature and variable velocity, and variable temperature and fixed mass flow rate, respectively. On the previous phase, it was found that the flow rate in a system played an important role for the flow sensor (piezoelectric) that was being used for the experimentation.

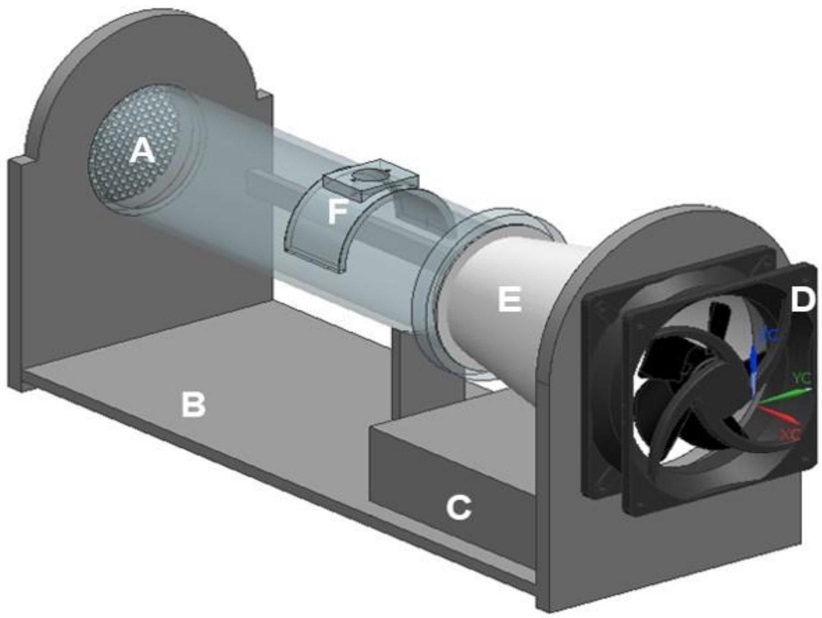



| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| Test chamber | DC Axial Fans | Delivery Tube | Reduction Coupling | Flow Straightener | Sensing Element & mount | Support |

*Figure 19 Experimental apparatus with rectangular test section (RTS)*

The results of the first phase involved the use of two different tests setups, a rectangular and cylindrical, *Figure 19 and Figure 20,* respectively. The rectangular setup, *Figure 19,* was built with two inlets and one outlet and a box in the center were the sensor is located. These two inlets have a fan each with a reduction from the fan to an acrylic pipe that is then attached to the box where the sensor is inserted. Then, another test setup, *Figure 20,* was utilized on the first phase were it only uses a one-direction flow, one inlet and one outlet. It is like the rectangular setup with the difference that the sensor is located at different zone of the test sections.

Here, on these two setups the flow rate was being increased by adjusting the speeds of the




| A | B | C | D | E | F |
|---|---|---|---|---|---|
| Flow Straighter | Base | Controller | DC axial fan | Reduction coupling | Sensing element and mount |

*Figure 20 Experimental apparatus with circular test section (CTS)*

fans. Compared to the second phase, the flow rate on the system was set to be fixed and the variable was the temperature. This was done to analyze how the signal of the flow sensor was being affected by different circumstances, flow rate and temperature, and see which plays a higher effect on the sensor. Some of the results from the phase 1 are represented on *Figure 21* and *Figure 22*. The first figure, *Figure 21*, represents the results of the flow sensor signal at the cylindrical setup with variation on velocities. Then, *Figure 22*, is the representation of the results for the sensor at the rectangular setup. All these results are recorded under room temperature.

On the other hand, *Figure 22* demonstrates how the signal is affected by the change in temperature and the same mass flow rate.

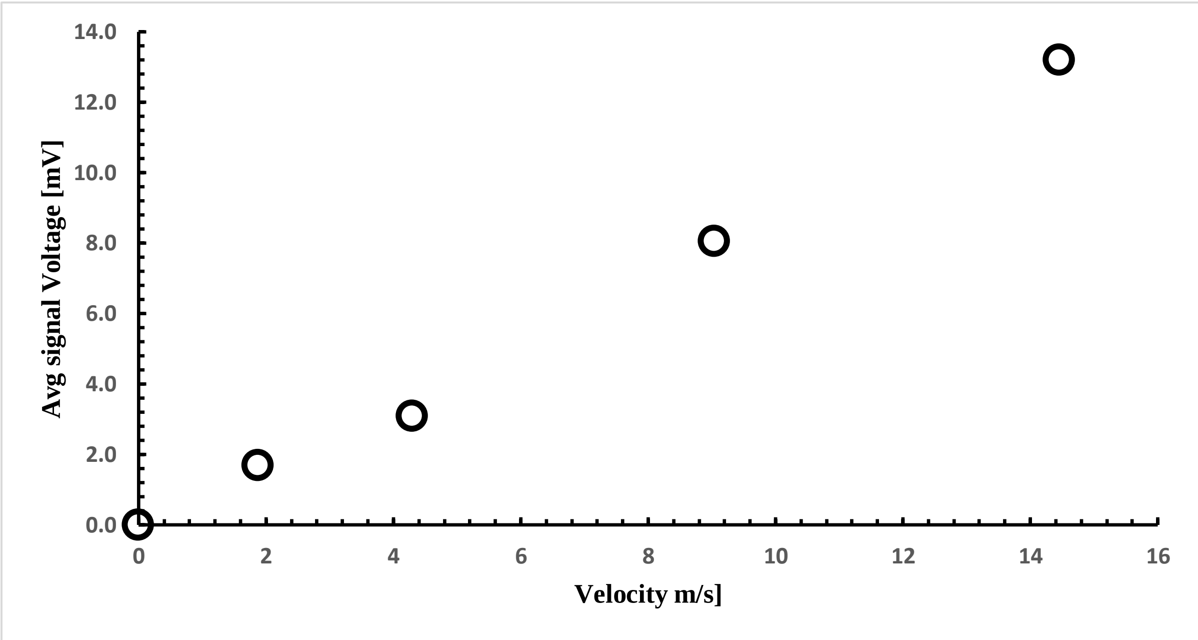



*Figure 21 Piezo-J output voltage at the different tested velocities in the circular test section setup*

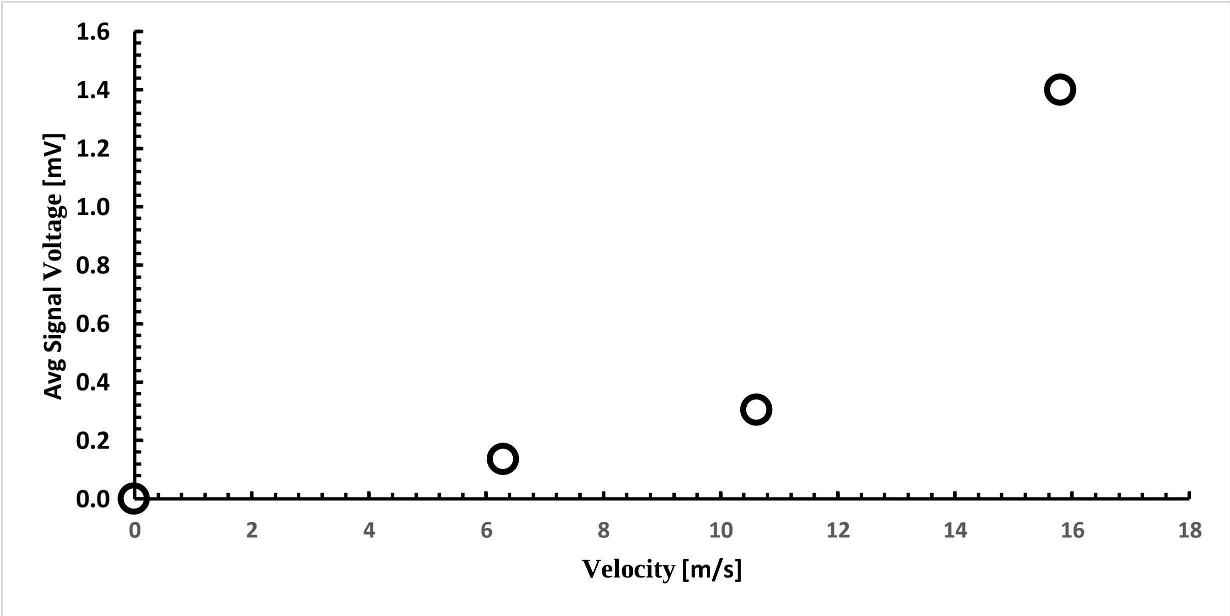



*Figure 22 Piezo-J output voltage at the different tested velocities in the rectangular test section setup*

This plot demonstrates that the temperature and the voltage have a correlation between them. After analyzing the behavior previously shown, the next step was to compare the change in signal once the temperature starts to increase. Also, *Figure 22,* is a plot that compares these changes and validates the idea that the higher the temperature is, the higher signal obtained from the sensor.

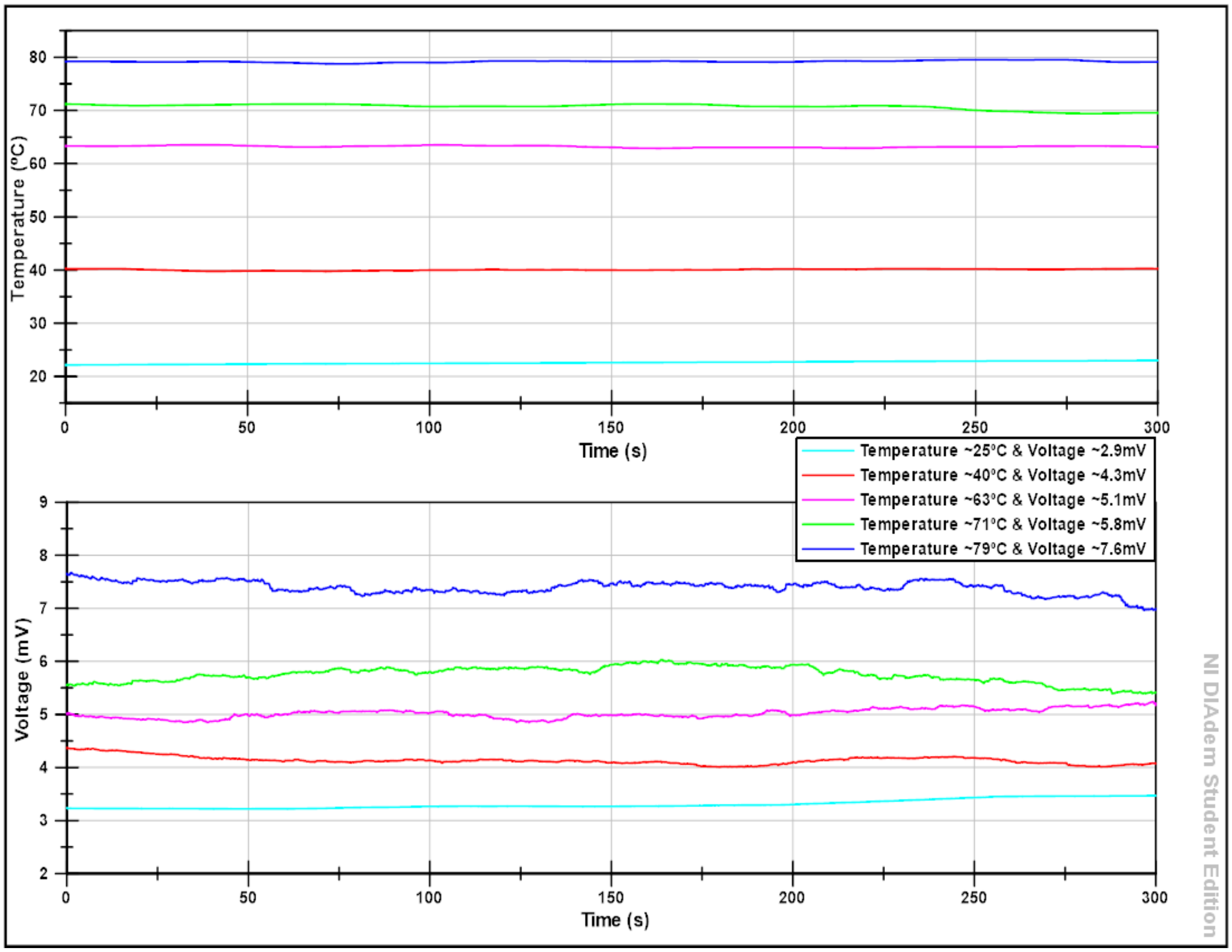



*Figure 23 Piezoelectric Voltage Signal at Different Temperatures*

Therefore, to see if the effects of temperature where greater than at room temperature, *Figures 21-22,* were compared. After comparing all three figures, it was demonstrated that at higher temperature, the signal from the flow sensor is higher.

To demonstrate it, the mass flow rate of the phase 2 results was used to calculate an approximate velocity at room temperature to compare the results from all 3 experiments at the same mass flow rate. From this calculation, the changes in areas and densities were considered for the experiments on phase 1 to get the signal at the obtained velocities, *Figure 21-22,* and compared to the signal obtained at phase 2 high temperature, *Figure 23.*

### 3.2 DISCUSSION

All the test conducted during this investigation, demonstrated that the temperature is a big factor to obtain a higher signal. This is demonstrated by comparing the results at elevated temperatures previously mentioned with the signal obtained from phase 1 at a low temperature. After comparing all experiments, the difference from the experiments was quite significant for one experiment and about the same for another. The signal obtained at a high temperature of 79ºC from phase 2 to the rectangular setup from phase 1 is higher by around 15 times. However, the signal using this same temperature compared to the cylindrical test set up from phase 1 is the same. Therefore, the signal of the flow sensor from the rectangular setup to phase 2 is smaller even though the mass flow rate is the same, but on the other experiment comparison, the signal is the same meaning that the temperature does not affect the signal, but the mass flow rate does. However, on the first phase, the signal was only increased when the velocity was increased meaning that the mass flow rate was higher, but on the second phase, the mass flow rate was kept constant and the variation in velocities from all the experiments recorded is about 1m/s and the increment in signal is significantly considered.

To verify if this was caused by temperature/flow and not because of the material properties, the research previously mentioned were taken into consideration. On these investigations it was observed that the effect of temperature is a factor for the sensors and its properties, but according to the results, it is not clear if the signal (voltage) is affected by this change. Zhang and Yu mentioned that the materials properties of piezoelectric sensors are affected by high temperatures, but this is when the curie temperature is reached or near reaching it. The properties affected by the changes are less sensitivity, mechanical properties, depolarization and piezoelectricity lost, durability and phase transition [10]. Tzou and Ye demonstrated that pyroelectric (direct temperature effect) effect on PZT materials is insignificant, but the thermal strain effect (indirect temperature effect) is significant. At a controlled plate, the thermal deflection is almost totally controlled compared to when one side of the plate is hotter than the other [12]. Birman concluded that it is impossible to predict if elevated temperature will result in the increase or decrease of the voltage in the sensor. The changes in voltage depend on piezoelectric material, and properties, lay-up, and geometry [14]. According to Upadhye, Vaishali, and Agashe investigation, is that the resonant frequency is affected by temperature and pressure. When temperature is involved, resonant frequency decreases if temperature increases since the piezoelectric element is directly proportional to the stiffness constant. On the other hand, when pressure is involved it is observed that resonant frequency increases when pressure increases. That is because the resonant frequency is inversely proportional to the thickness of the piezoelectric element [15]. Miclea et.al analyzed the behavior of a soft piezoelectric material (PZT) parameters at temperatures range of 0ºC - 350ºC. The analyzed parameters were the electromechanical coupling factor $k_p$, the mechanical quality factor $Q_m$, the dielectric permittivity $\varepsilon$, the loss tangent $\delta$, the piezoelectric charge constants $d_{33}$ and $d_{31}$, and the voltage constants $g_{33}$ and $g_{31}$. After conducting the experiments, it was concluded that the parameters does not present any variations on the piezoelectric sensor on temperatures below 150ºC, between 150ºC and 250ºC it was observed that the performance decreased slightly, but not to be considered an essential effect, and over 250ºC, the piezoelectric cannot longer be used since the parameters drastically and irreversibly decreased [23].

For the purposes of this investigation, this demonstrates that a piezoelectric sensor made of PZT produces a higher signal under high temperature applications and that the material properties effects do not affect the voltage generated during the experiments. This can be useful at the time to harvest energy and store it to feed other devices or simply analyze the data, or detect a possible harm situation in a system since it can be specified the ideal signal and once an anomaly happens, this can be stopped before a more catastrophic event occurs. To make sure that this was more detailed, clear, and to validate the previous plots and ideas, every experiment was taken as a unique test. After processing the data from all the conducted experiments, the values that were in a certain range were averaged, the points that were off by a huge difference were considered failed experiments and removed from the final analysis. All this was done with the idea to have a better picture of how the voltage was behaving with the change in temperature. *Figure 24* is the result after processing all the experiments. This plot can be used to predict the approximate values of the voltage produced by the sensor at a certain temperature. It has an exponential trendline that is obtained from the initial temperature to the maximum temperature recorded during the experiments. If the initial temperature is removed, the relationship between voltage and temperature is close to be linear. The magnitude of signal obtained from the minimum and maximum temperatures recorded have a huge difference between them, 6mV and 62.8ºC, respectively. However, once the temperature starts to increase, the signal keeps increasing, but the difference is not as big from one temperature to another compared to the initial and final signals recorded. This might be a material effect, where the rate at elevated temperatures is not to apart from another since they are closer to the curie temperature of the sensor. Also, from the plot

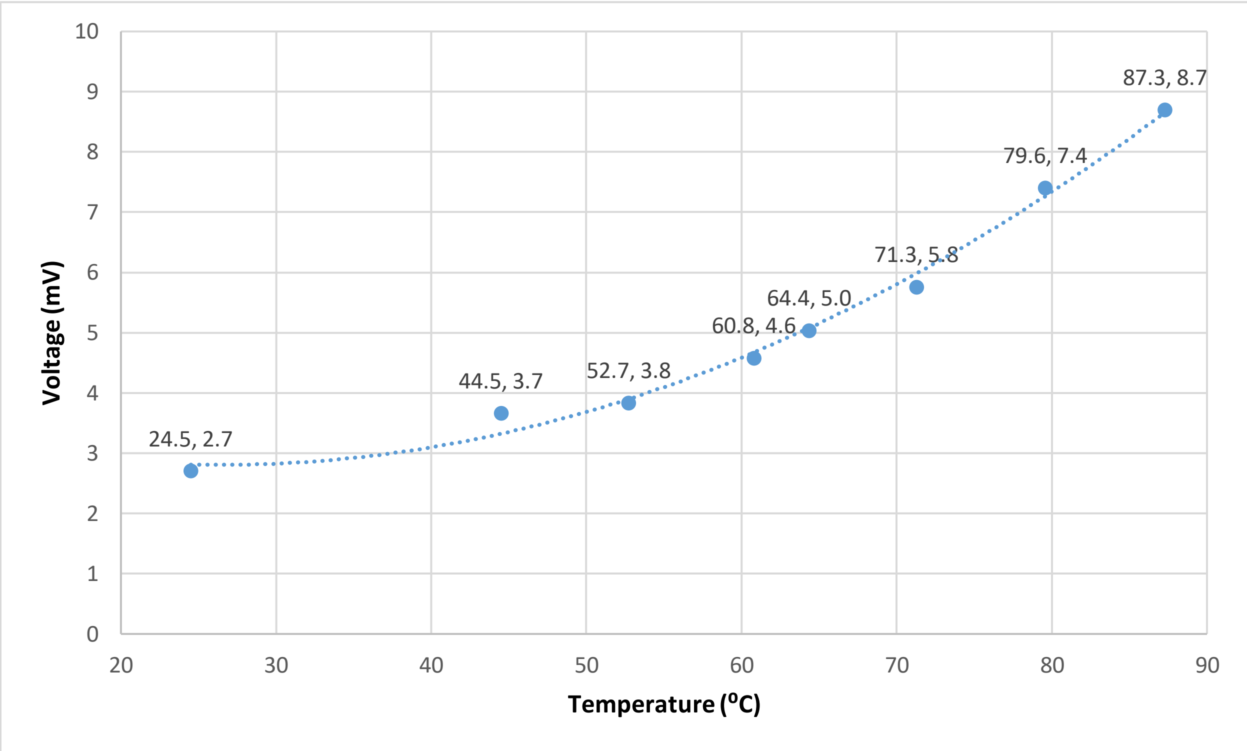



*Figure 24 Final Representation of the Effect of Temperature on a Piezoelectric Signal*

it can be noticed that the signal is increasing, and it is not clear if the temperature is going to be constant at a certain temperature or if this is just going to keep increasing until the curie temperature is reached. Unfortunately, this was not able to be tested and analyzed since the maximum temperature that was used on this experiment was limited.

# Chapter 4: Summary and Future work

## 4.1. Summary and Conclusions

There have been multiple researchers studying piezoelectric sensors and how temperature impacts the amount of voltage produced by the material. Previous investigations in literature have found and included studies on vibrations and how piezoelectric properties get affected during conducted tests at high temperatures. In this study, the piezoelectric material will be implemented on system where air is the fluid and then this is heated to different temperatures below the Tc of the material. The objective of this research is to quantify the signal (voltage) of a piezoelectric sensor at elevated fluid temperatures and compare with results at room temperature and previous phase. In order to prove if the piezo electric sensor can be used in these situations, a set up was designed and build where the sensor was inserted and it faced different changes in temperature to see how the signal is affected. The following points show the main contributions to this study:

- An elevated temperature experimental setup was designed and built capable of having temperatures in a range of 25ºC-90ºC to run the experiments and analyze the effects on the signal of the sensor.
- The effects of velocity on the piezoelectric sensor were measured at room temperature 25ºC and at a fix mass flow rate of 0.07kg/s using a flow meter, thermocouple and a DAQ system to get the signal.
- The effects of temperature on the piezoelectric sensor were recorded at different temperatures in the range of 30ºC-90ºC by using heaters.
- Results of the signal from this phase are 15 times higher than previous phase in the rectangular set-up and the same compared to the circular set-up. However, the

maximum velocity for this phase is 4.5 times lower compared to the one used on the previous phase on both experiments.

- The piezoelectric sensor signal is affected by the change in temperature. This suggests that the sensor can be used in a system that involves high temperature and still produce an output signal.
- It is observed that when the temperature of the system increases, the piezoelectric sensor's signal is increasing too. Therefore, at high temperatures, the signal produced by the sensor is higher that the signal at lower temperatures. However, the signal has not a linear relation with temperature, but an exponential one.

### 4.2. FUTURE WORK

It is recommended that higher temperatures that the ones used in this study are used to know how the sensor will behave once the temperature starts to reach the curie temperature of the sensor. Also, the use of different piezoelectric materials to see if this behavior is only reflected in PZT or if it is the same for any kind of piezoelectric materials. Therefore, the next step will be implementing this sensor in a HYPER Facility were a high temperature (200ºC) is involved and at the same time, multiple sensors of different materials can be tested. After analyzing the results of this experimentation, it will be possible to determine if piezoelectric sensors can be implemented in high temperature components and, if they can predict and prevent a situation such as surge and stall.

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# Appendix

## THEORY

The piezoelectric sensors have an electro-mechanical relation that is defined by two equations, Eqns. (1) and (2) represent this relationship [19].

$$\varepsilon_i = S_{ij}^{D}\sigma_j + d_{mi}E_m \tag{1}$$

$$D_m = d_{mi}\sigma_i + \xi_{ik}^{\sigma}E_k \tag{2}$$

Where the variables refer as follow, mechanical strain vector (ε), compliance coefficient matrix (S), strain constant matrix (d), dielectric displacement vector (D), mechanical stress vector (σ), applied electric field vector (E), permittivity ($\xi$). Once the piezoelectric sensor is excited by the mechanical force, this causes it to generate a stress and therefore, a voltage signal is generated. This is the direct effect caused on the sensor. To find the voltage generated, Eq. (3) can be used to determine it:

$$V_p = \frac{q}{C} \tag{3}$$

Where $C$ is capacitance of the sensor. For this study, the temperature of the sensor is the main factor as well as the mass flow rate that is being input into the system so the needed temperatures can be achieved. Because of these, the following equations were used to determine the different temperatures that could be achieved by the heaters and the mass flow rate produced by the fan. First, the power equation was used to calculate that the power source was proportionating and do an inverse relation to find the needed mass flow rate, Eq. (4) [20].

$$P = vI \tag{4}$$

Where (v) is the voltage from the source and (I) is the current. From here, we can say that the power is equal to the heat transfer (Q) and use this equation to find the mass flow rate at a given temperature, Eq. (5) is the heat transfer equation [21].

$$Q = \dot{m} C_P \Delta T \tag{5}$$

Where ($\dot{m}$) is mass flow rate to be determined, ($C_P$) is the heat capacity of the fluid and ($\Delta T$) is the difference in temperature. For the difference in temperature and the performed calculations for this study, $T_1$ is 22ºC that is also room temperature and $T_2$ is the expected or needed temperature for the research. Then, since the density of the fluid is constant and the area of the system too, the mass flow rate equation, Eq. (6), is set to find the velocity that is needed to achieve $T_2$ [22].

$$\dot{m} = \rho V A \tag{6}$$

The area of the pipe where the sensor will be located is represented by (A), the velocity needed to achieve the expected temperature is (V), and the density is ($\rho$). Different calculations were made with a variety of areas, temperatures, and mass flow rate to find the most realistic one and be able to build the system for this study.

After all these calculations, other equations were used to calculate the pressure drop throughout the build system and make sure that the velocity was going to be as previously calculated. The following equations were used. The mass flow rate equation, Eq. (7), was used to calculate the velocity (V) of the fan with a given mass flow rate ($\dot{\forall}$) and area (A).

$$\dot{\forall} = AV \tag{7}$$

Then, Ideal Gas Law Equation Eq. (8), was used to be able to obtain the pressure in different regions of the system with the change in velocity due to the change in areas.

$$P = \rho R T \tag{8}$$

Where P is the pressure at a specific point, V is the velocity, $\rho$ is the density of the fluid and it remains constant, R is the air constant value and T is the temperature. Also, Reynolds Number equation was used to see the type of flow, laminar or turbulent, Eq. (9).

$$R_e = \frac{\mathrm{VD}}{\nu} \tag{9}$$

In this equation, V is the final velocity in the system, D is the diameter and $\nu$ is the kinematic viscosity of air at a given temperature. Then, two more equations were used to obtain the total pressure drop across the system by using the modified Bernoulli's Equation where the major and minor pressure losses were considered and the Swamee-Jain Friction Factor, Eqns. (10) and (11).

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 + h_l \tag{10}$$

$$f = 0.25\left[log\left(\frac{\frac{\varepsilon}{D}}{3.7}\right) + \left(\frac{5.74}{Re^{0.9}}\right)\right]^{-2} \tag{11}$$

For Eq. (10) the head loss ($h_l$) includes the minor and major pressure losses throughout the system. This term is formed by the minor and major losses that by Eqs. (12) and (13). On Eq. (11), the $f$ is the Darcy Friction Factor, $\varepsilon$ is the specific roughness pipe and it depends on the material, D is the diameter and Re is the Reynolds Number.

$$h_{l\_minor} = K_l \frac{V^2}{2g} \tag{12}$$

$$h_{l\_major} = f \frac{LV^2}{D2g} \tag{13}$$

Where $K_l$ stands for the loss coefficient at a given angle, g is the gravity, and L the length of the pipe. All these equations played a big roll to make this study possible.

## Curriculum Vita

My name is Lyan Eduardo Gutierrez Hernandez, I obtained my bachelors in Mechanical Engineering at The University of Texas at El Paso (UTEP) in 2018. Then, right after graduating, I got accepted into a Master's Program at UTEP in Mechanical Engineering where I worked on my Thesis "Effect of Temperature on a Piezoelectric Mass Flow Rate Sensor Signal".

During my career path as a graduate student, I had the opportunity to work as a Graduate Teacher Assistant (TA) and Graduate Research Assistant (RA). For my TA position, I assisted Dr. Khan in the Mechanical Engineering Department from August 2018 – August 2019 where I assisted him with the preparation and presentation of the class, projects, grading exams and tutoring office hours for the students. Then, I had the opportunity to work as a Research Assistant from December 2018 – December 2020 under the guidance of Dr. Love in the Mechanical Engineering Department. In this position, I did research and leadership activities that involved leading a team to work on hand calculations, PDR, assembly processes, testing, data collection, validation and analysis.

My awards during my bachelors and master programs are, Dean's List for the Mechanical Engineering Department 2014-2018, Top 10% Senior Luncheon for the Mechanical Engineering Department May 2018, Graduated with Honors Cum Laude May 2018, and IME Becas Scholarship from The University of Texas at El Paso/Institute for Mexicans Abroad on August 2018.

I was part of the Society of Hispanic Professional Engineers (SHPE) where I had the opportunity to be part of multiple events at UTEP, and attended to a conference at Phoenix, AZ on 2019 where I not only had the opportunity to know more about this society, but to be a volunteer at it.