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Development of Injection Molding Pressure Monitoring System Using Piezoelectric Sensor

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DEVELOPMENT OF INJECTION MOLDING PRESSURE MONITORING SYSTEM USING PIEZOELECTRIC SENSOR

A Thesis

by

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ABSTRACT

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Injection molding is one of the most popular techniques for global plastic production. With this automation technique, the plastic product can be manufactured at a low cost with a complex geometrical shape. A manufacturing process with the high productivity of an injection molding machine depends on molding pressure and temperature inside the mold cavity. In this research, an experimental work is performed to determine a process monitoring system using asynchronous data acquisition, through the incorporation of a wired piezo-ceramic sensor to acquire pressure of injection molding system. This piezoelectric sensor is designed in such a way that, a Bluetooth device can be connected with a sensor and can take live data reading of parameters from the running molding machine.

Keywords: injection molding; process monitoring; piezo sensor

DEDICATION

I dedicate my work to my parents, my wife, and my son.

ACKNOWLEDGMENTS

I would like to express my deep gratitude to my supervisor, Dr. Kye Hwan Lee, for his valuable guidance, suggestion, advice, and support through my master's study. I am also grateful to my thesis advisory committee Dr. Heinrich Foltz, and Dr. Rajiv Nambiar
for their valuable advice.

Most of the experiments in this dissertation were conducted in the Advanced Machining Lab at the University of Texas Rio Grande Valley. Some experiments were conducted at the Electrical Lab at UTRGV. I am grateful to have the privilege to work in this facility. I would particularly like to thank Jerry Ozuna, as I have learned Code composer from him. In addition, I am grateful to Hector Arteaga and Olumide for their practical assistance on Injection Molding machine operation and Mold flow simulation respectively. I want to thank Al Mazedur Rahman, Wasif Zaman Jitu, Abu Musa Abdullah Sourav, Fazle Rabby, and Zubair Zuven for making my journey smooth in UTRGV.

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CHAPTER I

INTRODUCTION

Manufacturing Industries are facing significant challenges to compete globally for meeting constantly varying, detailed requirements of existing and prospective customers. High features, market value, production time, and impact on the environment are some of the important concerns that all big industries should consider for remaining economical in this widespread market(Gupta et al., 2015). For these reasons, product design and material selections are the major focus area for any type of manufacturing industry. Among different types of materials, plastic became a very popular one because of its availability, low cost, recycling feature, ease of handling, etc. Though plastic originally represents the term “Pliable and easily shaped”, now it is considered as a category of materials named polymer("<history-of-plastics.pdf>,"). From the early 1970, the use of plastic as an engineering material has increased rapidly(Wang, 1992). Now, among all of the manufacturing industries, the plastics industry stands third in the United States according to the Society of the Plastics Industry (SPI) (Zhao et al., 2020). To produce these large scales of plastic products, there are several polymer-processing methods. Among them, injection molding processed more than one-third of all thermoplastic materials (Zhou, 2013). It is extensively used for high productivity, efficiency, and manufacturability to produce discrete plastic parts (Chen & Turng, 2005).

Injection molding process is a high speed, automated process which can produce either very small or very large parts with easy to very complex geometries. It is a complex process of sequential phases of mold filling, packing, holding, cooling, and part ejection (Malloy, 2012). During the entire process, the polymeris faces significant and dynamic changes in different stages of pressure and temperature. It is essential to know for the manufacturers that how various conditions of process parameters can affect the final product's quality(Fetecau, 2014). One of the major process parameters cavity pressure has a high influence on the injection molding process as it is a reliable indicator of shrinkage, warpage, thickness, and weight(Guan, 2013; Zhao et al., 2020).To know the final product's performance, a manufacturer needs to have an accurate cavity pressure curve which is a key indication throughout the injection mold process (Zamani et al., 2014). To ensure product quality, this process parameter should be monitored in an online automated process (Chen et al., 2018). The traditional injection molding operation mostly depends on the trial-and-error method and experienced operators. As a result, this method causes low production, less consistency, error repetition, and reliance on past knowledge (Zhao et al., 2020). To increase productivity, improve reliability and fulfill customer satisfaction, manufacturers are endeavoring to achieve fully automatic injection molding with online quality control (Gordon et al., 2015).

In recent times, the intelligent injection molding process is becoming more popular day by day. This process depends on the information collection technique in between the production cycle, computing methods of optimization, and controller variables of the process, which are mostly done by AI technology. Process sensing is the first stage of the intelligent injection molding process, where the main objective is to collect real-time detection of variables and to diagnose and guide the manufacturing process (Zhao et al., 2020). The process data inside the injection molding cavity can be achieved with the help of sensors which are very manageable currently, as these sensors have their individualities depending on the purpose (Ageyeva et al., 2019). Although various types of sensing techniques have been used to measure the mold cavity pressure, most of them require a wired power source for sensing and data transmission. Consequently, these sensors required drilling through the complex structure of the mold and cooling lines for placement.

In this paper, a low-cost pressure sensing technology is developed in such a way that it can be embedded inside the injection mold structure to measure the pressure of the mold cavity and have the facility of wireless data transmission to a Bluetooth device. A piezo ceramic disk is used as a physical sensing element. To facilitate data transmission from the mold cavity, a high-precision ADC Launchpad is used to transmit data to a Bluetooth device located outside of the mold structure where there is no space limitation. As the sensor is directly connected to the mold cavity the sensing process will have less electrical or mechanical noise. Furthermore, An experimental study has been done on an Injection molding machine “BOY 22 A Pro” to verify the sensing technique and data transmission.

CHAPTER II

LITERATURE REVIEW

Injection molding is a widely used manufacturing technique to fabricate thermoplastic parts. It is a complex process with three basic components: the injection unit, the mold, and the clamping system. The injection unit prepares the proper plastic melt and transfers the melt into the mold. The clamping system closes and opens the mold (Rosato & Rosato, 2012). In this way, the plastic material changes its primary state to its final state. The quality of the final state mostly depends on plastic pallets, mold design, and various process parameters (Khosravani & Nasiri, 2019). For predicting the melting quality, various Pressure-Volume-Temperature (P-V-T) measurement methods have been applied(Wang et al., 2010). One of the investigations showed that high backpressure and high rotational speed enhance the quality of the final plastic product(Latif & Saidpour, 1997). Taguchi design method was implemented to know the effect of the backpressure, and barrel temperature on product quality with acrylonitrile butadiene styrene (ABS) material. From the result, it was found that product quality highly depends on back pressure and barrel temperature at slow rotational speed (Khoshooee & Coates, 1998). Many studies have shown that by controlling these parameters effectively it is possible to improve the consistency with quality for the final product (Yang et al., 2016). These process parameters are conventionally controlled with either operator’s own experience or with some statistical methods(Chen et al., 2019). Although the process parameters are precisely controlled, significant plastic quality variation is often observed. For these reasons, uninterrupted observation and controlling the molding process are mandatory for finding the root cause of a faulty condition in the process and to overcome the problematic situation(Kumar et al., 2020).

As injection molding is a rapid and high-pressure process, the cavity pressure at injection molding running time dramatically affects the properties of the product such as product warpage(Wang et al., 2010; Zhang et al., 2019). For this reason, it is important to get the accurate values of this process parameter. To collect accurate data for process monitoring several technologies are available. Among those, sensors are the most widely used technology. In this experiment, a wireless pressure sensing technique is used to collect pressure from the injection molding system. However, getting accurate values from the sensor is challenging as there are several issues to overcome inside the cavity of the injection molding machine. Firstly, with high melt pressure, the sensor head is not protected from corrosive surroundings and rapidly varying temperatures (Ageyeva et al., 2019). Moreover, due to high mold temperature, there is always a chance of sensor output variations as it is implanted inside the mold(Tifkitsis & Skordos, 2019). So, it is essential to choose the appropriate sensor for measuring the parameter during machine running conditions (Di Fratta et al., 2016).

The recent methods that are commonly used for sensing pressure include strain gauges, where characteristics of a material resistance are measured by deformation with pressure; piezoelectric or piezoresistive sensing effects; flexible membrane's using mechanical deflection in different load; capacitance of a diaphragm which deflects with pressure and vibration. Figure 1 shows the classification of pressure sensors. These commercial pressure sensors are widely used in injection molding systems to study the correlation between cavity pressure of ejection stage and final product quality (Zamani et al., 2014). Recently, a self-energized duel parameter sensor was used for injection molding process monitoring (Gao et al., 2008). For the sensing process of polymer injection molding, a high-temperature piezoelectric film ultrasonic transducer was introduced (Kobayashi et al., 2006). To detect the filling imbalance of the molding machine, one indirect pressure sensor under the lens core was used (Gim et al., 2015). In another study, a surface strain sensor and pressure sensor were used for precise cavity pressure distribution (Guan, 2013).

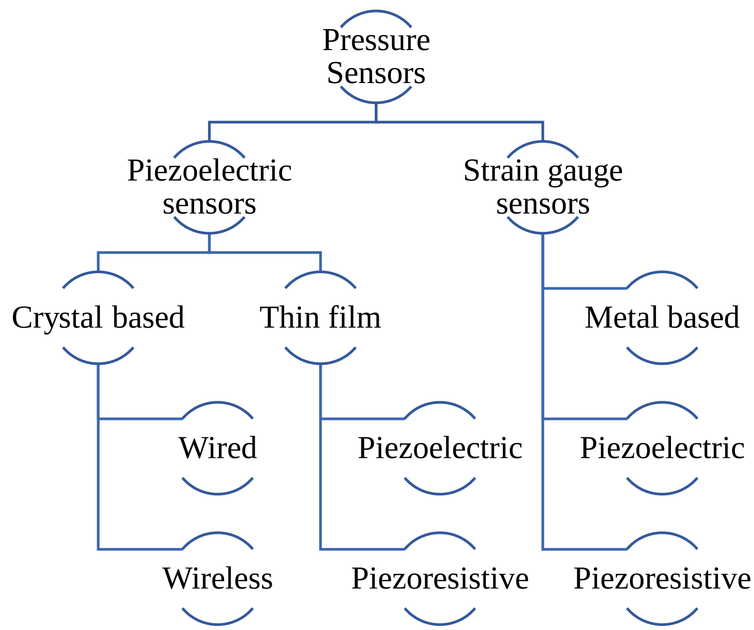


Figure 1: Classification of Pressure Sensors (Ageyeva et al., 2019)

In this paper, to get the pressure profile of the mold cavity, a low-cost piezoelectric disk was used to determine the value of the pressure at different pressure levels. Piezoelectric sensors produce an electric field depending on its body thickness, while it gets deformed by a dynamic external force, electrical charges move alongside to the pull direction creating a voltage (Tinoco et al., 2019). With a 1 to 15 mm sensor head, a piezo sensor can be operated in -40◦c to 400◦c and measure pressure up to 400 bar (Ageyeva et al., 2019). Direct, indirect, and contact-free pressure measurement techniques have been used for sensing pressure with piezo disks.

CHAPTER III

METHODOLOGY

3.1 Prototype Design

For the prototype design, a piezoelectric sensor (STEINER & MARTINS, INC. FLORIDA, USA) with 6*0.6mm R wire leads 3.4 MHZ was selected to collect the data points for pressure to voltage conversion. As the piezo sensor was plated with nickel, acid soldering flux was used for soldering the electrical wire with the sensor. As the output of the piezo disk was in the mili-volt range, around 150~250 mv, a single operational amplifier (TL081) was used to amplify the voltage of the piezo disk. Two resistors of 100 ohms and one kilo-ohm with an operational amplifier (supply voltage of 6V) were used for keeping the launchpad (communication device) safe from over-voltage.

Finally, this amplified voltage was used as an input for an integrated circuit which converts the electrical signal into a binary signal and transmits this signal to a device connected through Bluetooth. In this study, a SimpleLink™ MSP432P401R (Texas Instruments) high-precision ADC LaunchPad™ Development Kit with low energy enables dual-mode Bluetooth CC2650 module was used to transmit this data to a Bluetooth low energy mobile app named LightBlue® to get the live reading of the process parameters. Here, Code Composer Studio (Version 9.2.0) is used for controlling this data acquisition process.

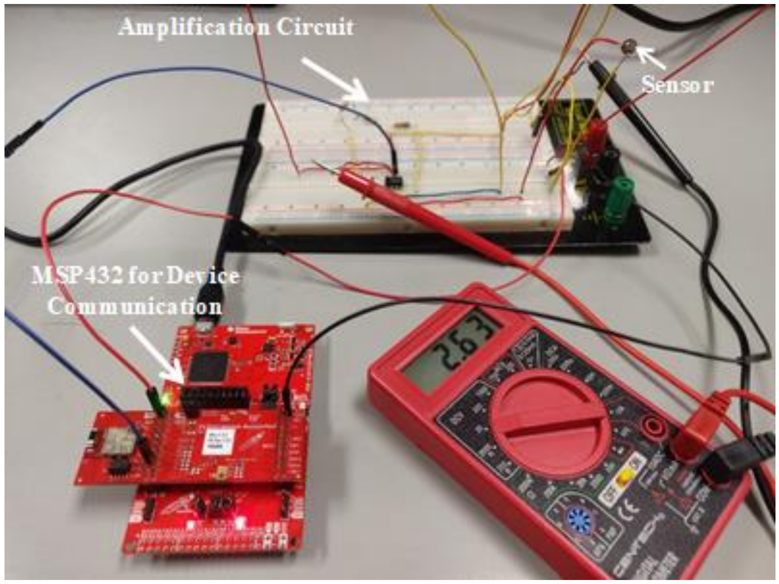


Figure 2: Prototype setup

Figure 3: Bluetooth device reading of the sensor

Figure 2 shows that a piezo disk is connected to the input of the amplifier circuit. In addition, the launchpad and multimeter are connected parallelly to the output of that circuit. The launchpad (MSP432) transmitted sensor data to a Bluetooth device using Light Blue mobile app.

The multimeter was used to verify and compare the Bluetooth device reading. The multimeter reading was 2.63 v (Figure 2) was obtained from the piezo disk after applying pressure (around 2 psi) and the Bluetooth device also showed the same result 2.63 v (Figure 3). Thus, it is concluded that the prototype design can successfully read the data from the sensor. However, this launchpad was unable to do wireless transmission of large data points (>20 bit) at a time. Data collection was done by fetching data from LaunchPad through a USB cable.

3.2 Sensor Installation

After designing the prototype successfully, the process was implemented on a test mold. The experimental trials considered a product specimen with a length of 161.89 mm, a central width of 10.83 mm, an end width of 16.89 mm, and a thickness of 3.18 mm (Figure 4). The runner diameter is 5 mm and the length (L shape) is 60 and 30 mm. The experiments were performed using homopolymer Polypropylene (Flint Hills P4G3A-052). Table 1 shows the equipment list and Table 2 shows the material properties and recommended processing conditions. These injection molding trials were performed using an injection molding machine (BOY 22 A Pro).

Table 1: Equipment list

Equipment Name	Model Name
Operational Amplifier	TL081, Texas Instrument
Development Kit	MSP432P401, Texas Instrument
Oscilloscope	Tektronix TDS 1000B
Function generator	BK Precision, Model 4045B
Multimeter	AM33D, AstroAI
Thermal Image gun	Fluke Thermal imager, Model Ti32

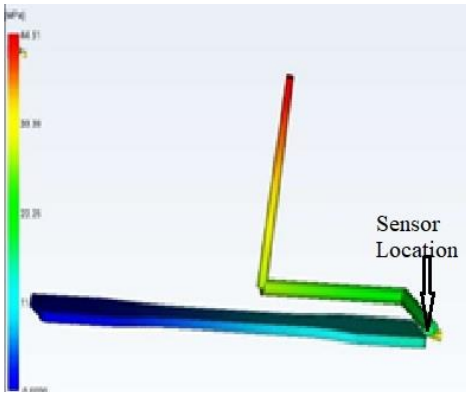


Figure 4: Product specimen from mold flow simulation

Table 2: Material properties and recommended processing conditions

Property	Polypropylene
Melt flow index	5.0 g/10 min
Tensile Strength	5370 psi
Density	0.0325 lb/in^3
Hardness	106 (R scale)
Processing Condition	
Mold Temperature	31^o C
Melt Temperature	204 ^{o} C

In this case, a 5*0.4 mm wired piezo disk (STEINER & MARTINS, INC. FLORIDA, USA) was used to measure mold cavity pressure and to avoid the soldering steps of the prototype design. This 5mm disk was installed in the mold runner path of the Injection molding machine. Figure 5 shows the location of the piezo sensor inside the mold. To keep the sensor safe from the molten plastic, Epoxy coating was used on top of the sensor head. When the pressure is applied to the piezo disk, it works as a pressure transducer and can able to register the change of pressure as a function of time. In addition, when pressure is transferred to the quartz measuring element, it produces an electrical charge proportional to the pressure.

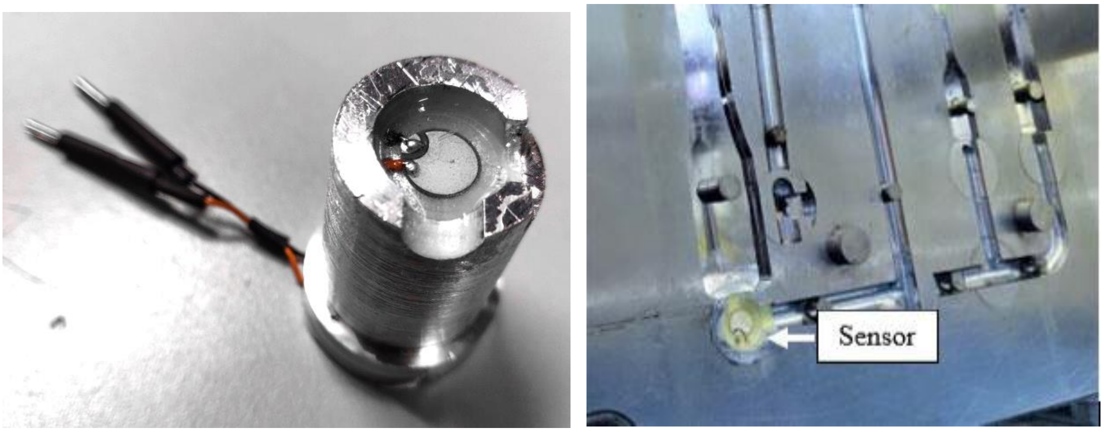


Figure 5: Installed Piezo disk inside mold

Inside the injection molding machine, polymer material passes from the hopper to the plasticization cylinder and changes into a molten state. Then this melted plastic is injected into the mold cavity through the runner and gate. After passing a complete cooling cycle the product is ejected from the mold. Whenever the mold closes, the sensor starts taking readings and stops when the mold is open. All the data sensed by the piezo disk was collected by an oscilloscope and the Launchpad (MSP432) parallelly.

3.3 Sampling accuracy analysis

In this study, for verifying the data collection accuracy of the launchpad (MSP432), an accuracy analysis was conducted. For this experimental run, a function generator (BK Precision, Model 4045B) was used with two input parameters: amplitude and frequency to evaluate the sampling performance. Figure 6,7, and 8 shows that at a fixed frequency of 100 Hz, 200 Hz, 300 Hz respectively, collected data from MSP432 matches with the amplitude value of the function generator at different voltage range. From these figures, it is concluded that the launchpad can take accurate data samples comparing with function generator data points.

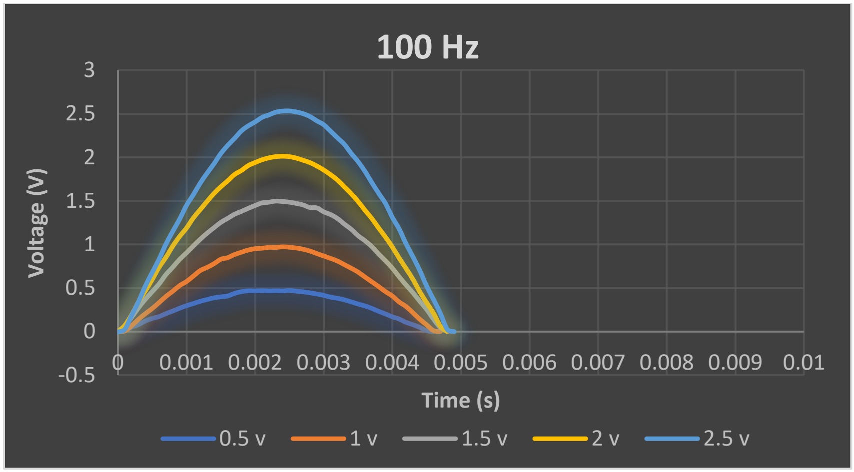


Figure 6: Voltage vs time curve with fixed frequency of 100Hz

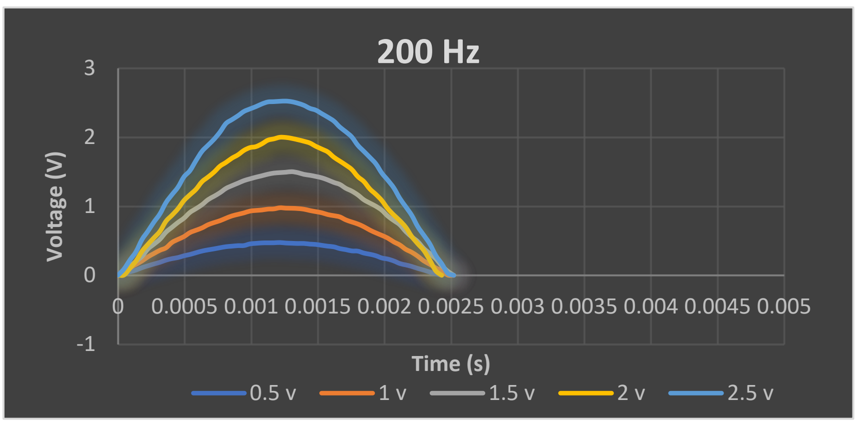


Figure 7: Voltage vs time curve with fixed frequency of 200Hz

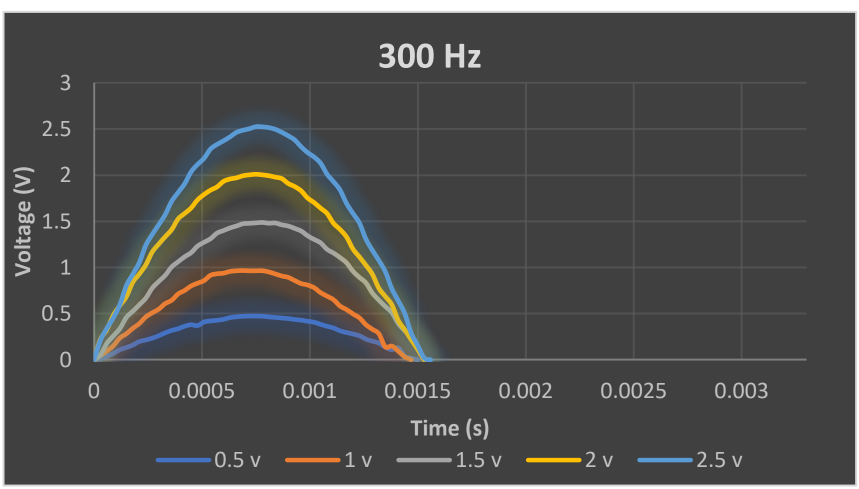


Figure 8: Voltage vs time curve with fixed frequency of 300Hz

3.4 Temperature Sensitivity

To observe the temperature sensitivity of the sensor, a heat gun was used for varying the sensor body temperature while applying fixed pressure on the surface of the piezo disk.

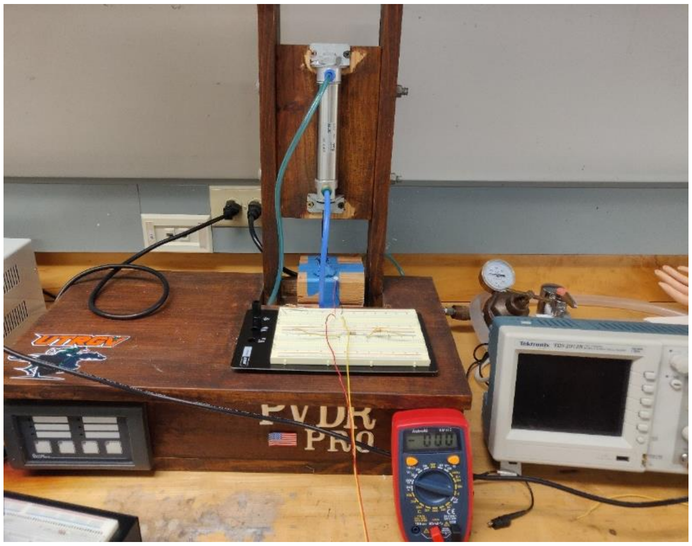


Figure 9: Pneumatic punch machine for generating pressure

In Figure 9, a pneumatic punch machine was used for constant pressure. A pressure gauge and a needle valve were used to keep the pressure at a constant rate. Figure 10 shows the thermal image of the sensor before (left) and after (right) applying heat. It was observed that when the temperature of the sensor body reached from 80˚F to 95˚F (using FLUKE thermal imager), the sensor gave the abnormal reading.

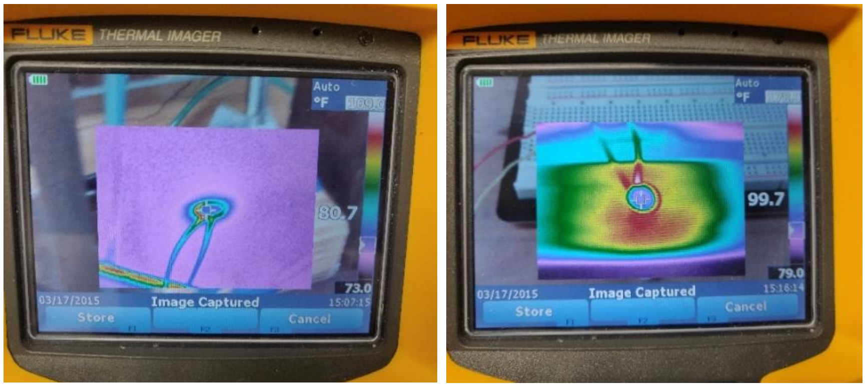


Figure 10: Thermal image of heated sensor

Table 3: Sensor output variation in different temperatures

Temperature	Voltage Average
75˚F	117.5 mv
85˚F	120 mv
95˚F	800 mv

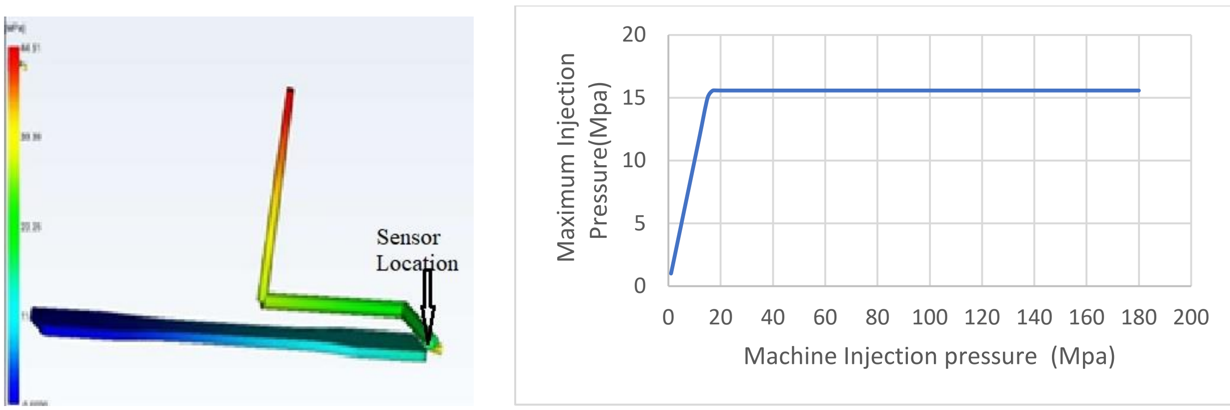
Table 3 shows that at constant pressure (2 Psi), the output voltage of the piezo disk was almost the same while changing the temperature from 75˚F to 85˚F. But the output voltage became unstable when the body temperature rises to more than 90˚F. At 95˚F of sensor body temperature, the output voltage was fluctuating from 500 -1100 mv, which concludes the sensor will not act properly if the body temperature is more than 90˚F. However, mold temperature was maintained at 87˚F during the entire experiment and no significant output shift was observed due to sensor body temperature. Temperature shifts should be considered for future development.

3.5 Voltage to Pressure Conversion

The sensor output was in voltage form. To get the pressure profile, voltage to pressure conversion is required. The co-efficient for converting the voltage into pressure is generated by the pressure conversion equation (1). This co-efficient was obtained from the comparison among the sensor output and the mold flow simulation output for a specific injection machine pressure.

$P = -$ dt .... Equation (1)

From equation (1), $-$



(a) (b)

Figure 11: Pressure profile from Mold Flow simulation

Figure 11 (a) shows simulated maximum injection pressure is 15.57 MPa when machine injection pressure is 45 MPa. Figure 11 (b) shows that from 17 MPa of machine injection pressure, the maximum injection pressure remains constant at 15.57 MPa. So, this is the maximum injection pressure that is used to calculate the value of α.

When machine injection pressure was 138 MPa,

$$Pmax = 15.57\ MPa, From\ mold\ flow\ simulation, figure\ 11$$

$$max \int V(\mathrm{t}) * dt = 9.84, from\ the\ positive\ cycle\ of\ the\ sensor\ output, figure\ 12$$

$$\alpha = (max \int V(\mathrm{t}) * dt)/Pmax = 9.84/15.57 = 0.631985$$

Finally, for this α, the sample data points of voltage were converted into pressure by using equation (1). Figure 15 shows the cavity pressure profile of the injection molding machine from oscilloscope and launchpad reading for machine injection pressure 138 MPa and α=0.631985.

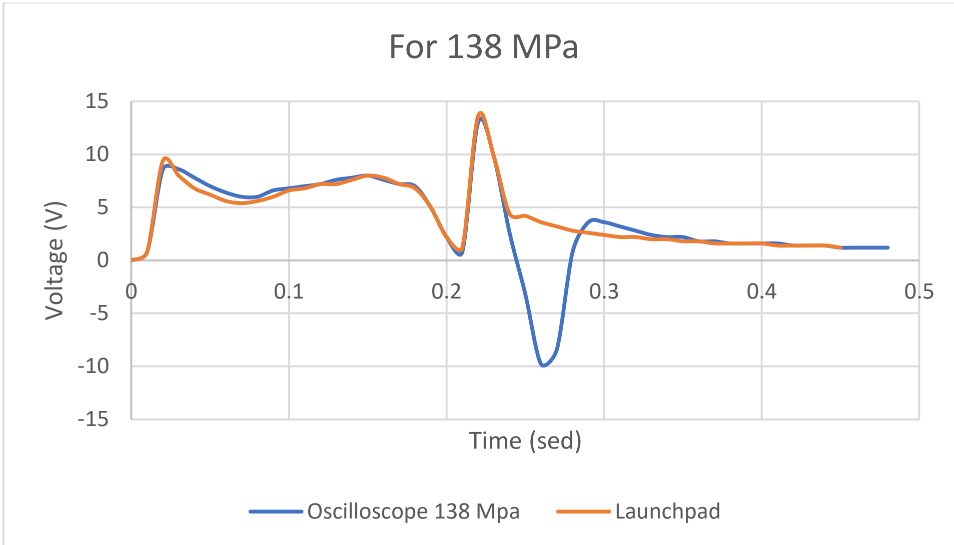


Figure 12: Voltage reading from Sensor when machine injection pressure was 138 MPa

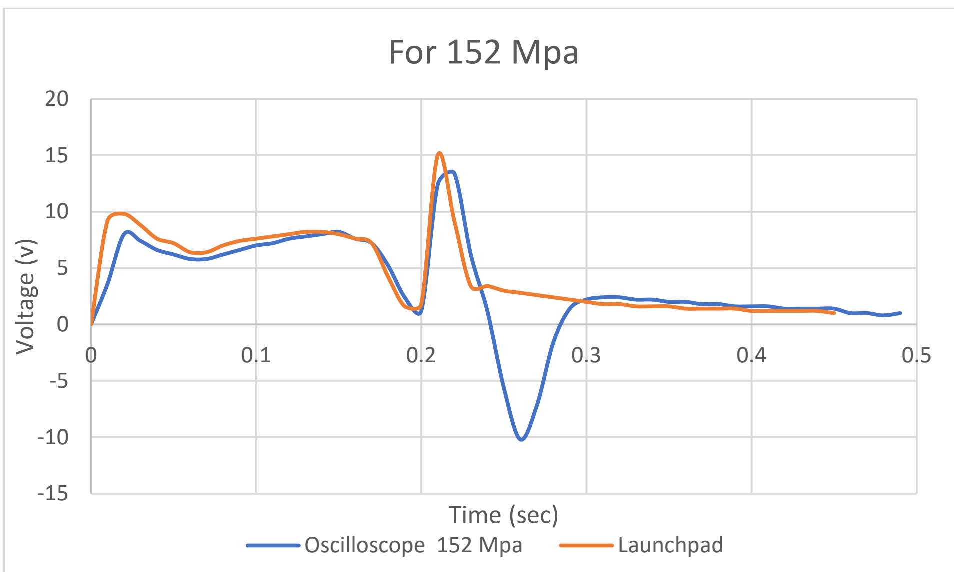


Figure 13: Voltage reading from Sensor when machine injection pressure was 152 MPa

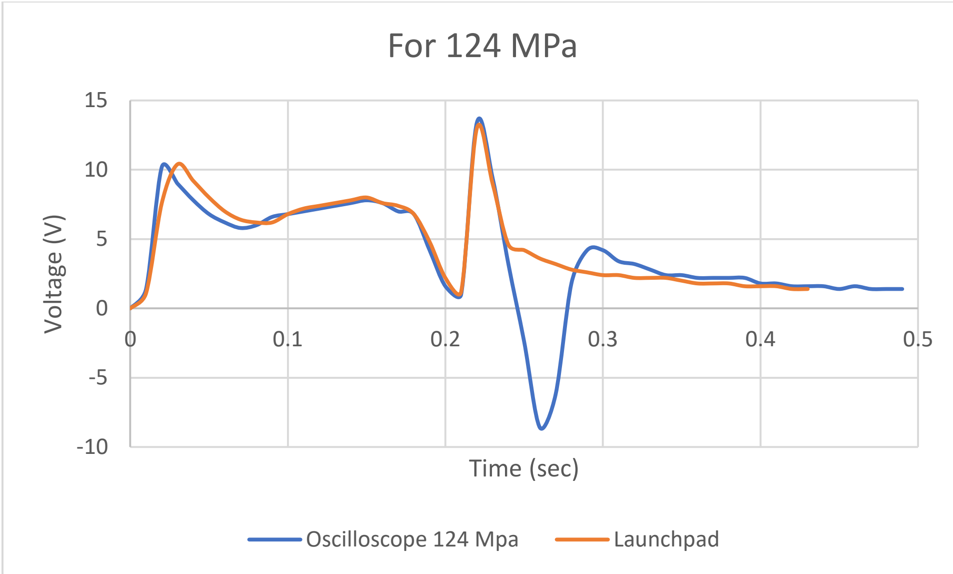


Figure 14: Voltage reading from Sensor when machine injection pressure was 124 MPa

Figure 12,13, and 14 shows the graphical view of the voltage reading from the sensor via Launchpad and Oscilloscope with a sampling rate of 100 Hz. Also, mold filling time is less than one second. These figures show that Launchpad only shows the positive voltage reading, whereas Oscilloscope reading has both positive and negative values. After 0. 25 second the Launchpad data goes downward and become flattened. It is a Launchpad design issue. It fails to record the maximum pressure as maximum cavity pressure should be found at the time when the positive cycle ends.

Figure 15 shows the pressure profile comparison between the Oscilloscope and Launchpad reading for 138 MPa machine injection pressure. It shows that oscilloscope reading gives maximum pressure at 0.26 sec. However, pressure value from launchpad reading keeps increasing as launchpad reading has no negative cycle. To draw a complete pressure profile, both positive and negative cycle of voltage is required. As a result, launchpad reading cannot provide a complete pressure profile.

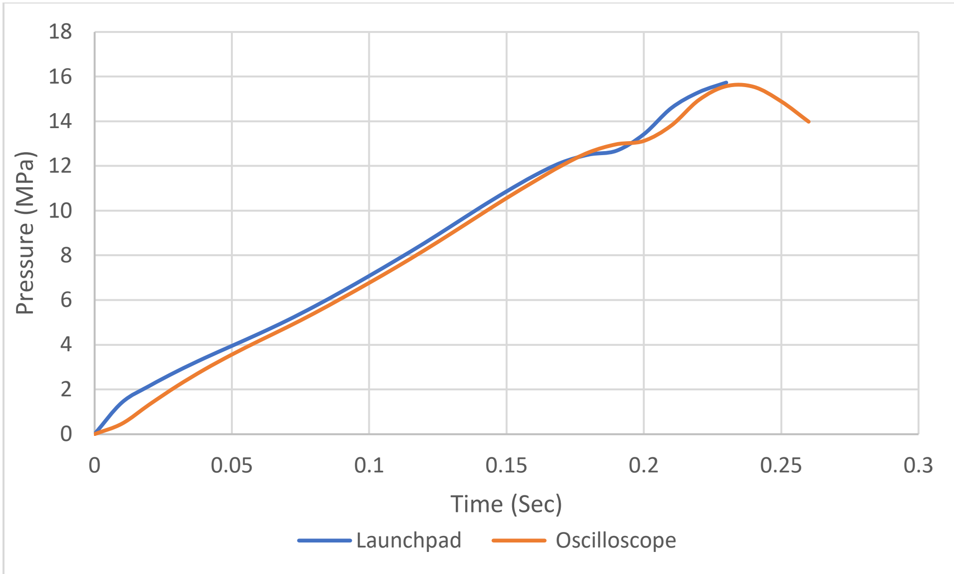


Figure 15: Cavity Pressure Profile when machine injection pressure was 138 MPa

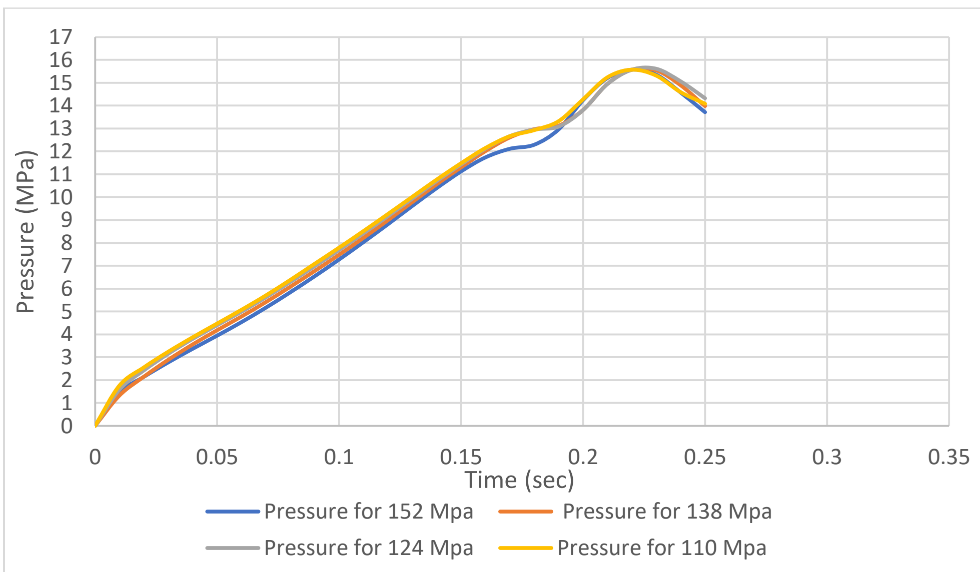


Figure 16: Cavity Pressure Profile from Oscilloscope data

Figure 16 shows the cavity pressure profile of the injection molding machine at different Machine Injection Pressure. These pressure values are calculated from the oscilloscope voltage reading. For each machine injection pressure, coefficient α is calculated individually at the endpoint of the positive voltage cycle where $\int V(\mathrm{t})$ is maximum. Overall, the injection pressure profile collected using a piezo sensor showed a good match with the injection pressure profile using conventional injection cavity pressure sensors.

Table 4: Pressure Conversion Coefficient at different Machine Injection Pressure

Machine Injection Pressure (MPa)	Pressure conversion coefficient α ($v*sec*MPa^{-1}$)
110	0.1049
124	0.1002
138	0.1000
152	0.1012
Average	0.1016
Standard Deviation	0.0023

Table 4 shows the variation of the Coefficient value at the different machine injection pressure. Ideally, pressure conversion coefficient α should remain constant over the pressure range. From Table 4, they showed an average of 0.1016 and a standard deviation of 0.0023 which means α is almost constant.

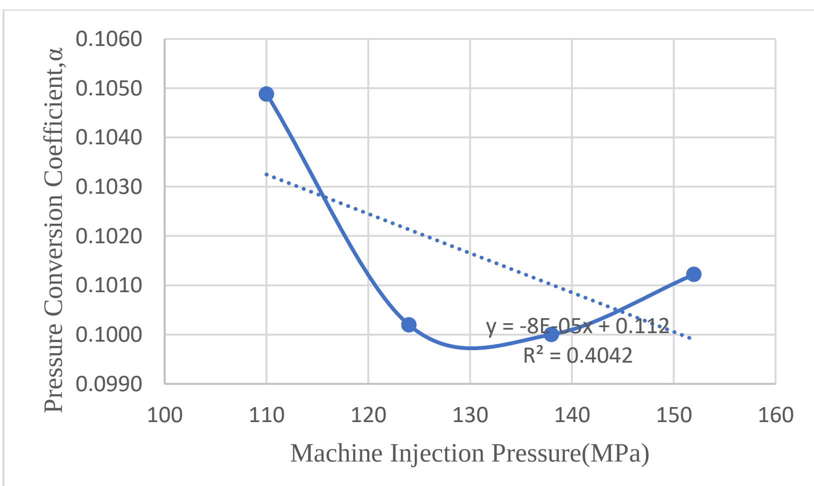


Figure 17: Pressure Conversion Coefficient at different Machine Injection Pressure

Figure 17 shows that the maximum deviation occurred when machine injection pressure was 110 MPa. As pressure conversion was done using $max \int V(\mathrm{t})dt$ at the endpoint of the positive cycle of the voltage reading, shifting of the cycle may change the value of α. Figure 18 shows that for different machine injection pressure, the positive cycle ending point is almost similar but some voltage reading fluctuation is found on the positive cycles. However, pressure measurement using piezo sensor and conventional sensor need to be performed. This deviation may come from sensor location and mold geometry which may lead to pressure drop and gives the same pressure reading within the ranges of injection pressures.

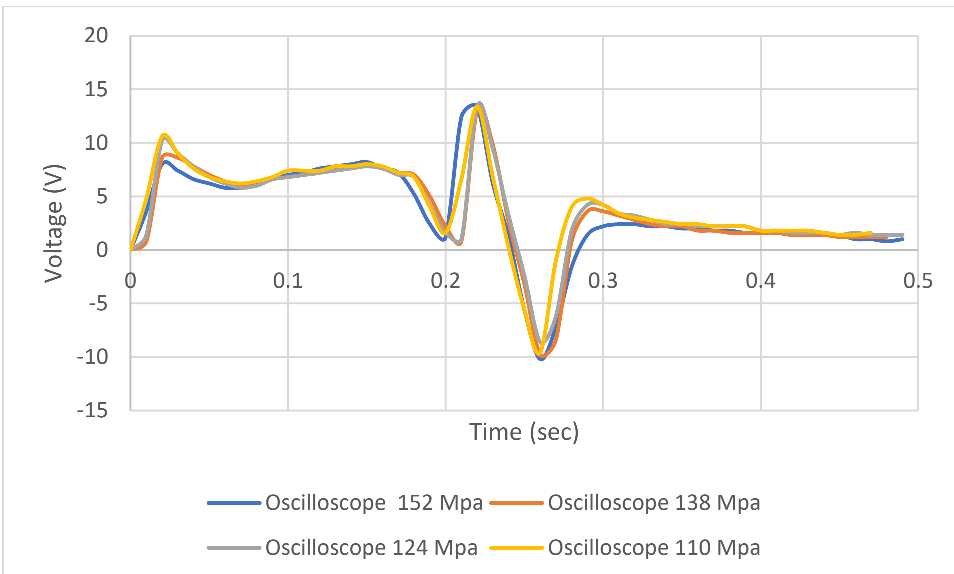


Figure 18: Voltage reading for different machine injection pressure

Another consideration is the calculated pressure conversion coefficient is based on Mold flow estimation, not from an actual pressure measurement. It is suggested that installing a calibrated conventional pressure transducer for actual pressure reading to calculate accurate pressure conversion factor.

CHAPTER IV

CONCLUSION

In this paper, a new low-cost method was proposed to measure the online cavity pressure of an injection molding process with a piezo sensor. This study combines physical sensing and data transmission of mold pressure. Based on the result attained from this experiment, the proposed piezo sensor can collect data from a running injection molding machine. This launchpad can only provide positive cycle reading which is not sufficient to draw the full pressure profile of the cavity. However, from the oscilloscope reading, the pressure profile was plotted. This injection pressure profile collected using a piezo sensor showed a good match with the injection pressure profile using conventional injection cavity pressure sensors.

Ideally, pressure conversion coefficient α should remain constant over the pressure range. In this study, Mold Flow simulation was used to calculate α, and a standard deviation of 0.0023 was observed which matches the ideal condition. However, to confirm that, it is necessary to install a conventional pressure transducer to calculate α and compare it with the previous value. In prototype design, wireless data transmission was successfully conducted. However, in the final study, wireless data transmission of a high amount of sample points of mold cavity pressure was not successful as more memory space was required within the proposed launchpad to transmit these high-volume data.

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