PYROELECTRIC CERAMICS AS TEMPERATURE SENSORS FOR ENERGY SYSTEM APPLICATIONS

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to my

family and my future wife

with love

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by

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Abstract

Temperature is continuously monitored in energy systems to ensure safe operation temperatures, increase efficiency and avoid high emissions. Most of energy systems operate at high temperature and harsh environments to achieve higher efficiencies, therefore temperature sensing devices that can operate under these conditions are highly desired. The interest has increased in temperature sensors capable to operate and in harsh environments and temperature sensors capable to transmit thermal information wirelessly. One of the solutions for developing harsh environment sensors is to use ceramic materials, especially functional ceramics such as pyroelectrics. Pyroelectric ceramics could be used to develop active sensors for both temperature and pressure due to their capabilities in coupling energy among mechanical, thermal, and electrical domains. In this study, two different pyroelectric materials were used to develop two different temperature sensors systems. First, a high temperature sensor was developed using a lithium niobate (LiNbO3) pyroelectric ceramic. With its Curie temperature of 1210 °C, lithium niobate is capable to maintain its pyroelectric properties at high temperature making it ideal for temperature sensing at high temperature applications. Lithium niobate has been studied previously in the attempt to use its pyroelectric current as the sensing mechanism to measure temperatures up to 500 °C. Pyroelectric coefficient of lithium niobate is a function of temperature as reported in a previous study, therefore a dynamic technique is utilized to measure the pyroelectric coefficient of the lithium niobate used in this study. The pyroelectric coefficient was successfully measured up to 500 °C with coefficients ranging from -8.5 x 10^{-5} C/m^2 °C at room temperature to -23.70 x 10^{-5} C/m^2 °C at 500 °C. The lithium niobate sensor was then tested at higher temperatures: 220 °C, 280 °C, 410 °C and 500 °C with 4.31 %, 2.1 %, 0.4 % and 0.6 % deviation respectively when compared with thermocouple measurements. The second phase of this study focused on developing a wireless temperature

sensor with lead zirconate titanate (PZT) as the pyroelectric material. This wireless temperature sensor consists of generating current by the PZT when exposed to a rate of temperature change with time, which was conducted to a built electromagnet to produce a magnetic field. The magnetic field was captured wirelessly with a milligaussmeter at a certain distance. Pyroelectric property of PZT ($-40x10^{-5}$ C/m^2 °C at 25 °C) is higher than that of the lithium niobate ($-8.5x10^{-5}$ C/m^2 °C at 25 °C), which was necessary to be able to generate the necessary pyroelectric current to make magnetic field detectable by the milligaussmeter. The electromagnet body was 3D printed with ABS material and surrounded with winding wire material. Before attempting a wireless temperature measurement, several attempts to measure the magnetic field at different distances away from the electromagnet were done. At the applied heating rates, the milligaussmeter was able to measure magnetic field up to 1.27 cm away from the electromagnet edge. A PZT sensor with a thickness of 0.1 cm was tested for use in the wireless temperature measurement configuration. For more accurate wireless temperature measurements, a similar pyroelectric coefficient measurement technique as used in phase one was done. The pyroelectric coefficient was found to increase from $-40x10^{-5}$ C/m^2 °C to $-71.84x10^{-5}$ C/m^2 °C from 25 °C to 122 °C, respectively. The PZT sensor was then tested for wireless temperature measurement at a distance of 1.27 cm at set temperatures of 100 °C, 150 °C, and 200 °C, and showed a maximum 10.47 % deviation when compared to thermocouple reading. In order to increase the distance that the wireless temperature sensor can read, a ferromagnetic material was placed inside the electromagnet. The sensor was tested for wireless temperature measurement at 1.27 cm, 2.54 cm and 3.81 cm with a maximum deviation of 13.4 %.

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Chapter 1: Introduction and Background

1.1 Introduction

Components in energy systems require continuous monitoring of temperature in order to maximize efficiency. Temperature is a thermodynamic property that can be measured, thus components can be pushed to maximum temperature where these can operate safely without compromising the system [1]. Furthermore, monitoring of temperature on specific components of a system is desired since an increase or decrease in temperature could potentially compromise mechanical or chemical properties of a material. It is known that mechanical properties such as toughness and strength are sacrificed when operation temperature fluctuates [2]. Therefore, continuous monitoring of temperature is essential for optimal functioning and safety of energy systems. Many components in energy generation systems can reach extreme temperatures where these can exceed 1000 °C, corrosive and high pressure environments. A device that can accurately measure temperature under these conditions is important to assure structural stability and prevent functionality failure [3-5]. Therefore, development of temperature sensors that can operate in harsh conditions and wireless temperature sensors are desired. These technologies could reduce the maintenance cost of sensor's components as well as their overall price. Small number of technologies can operate under these conditions while providing high reliability. For these reasons, a high temperature and wireless temperature sensors are being investigated in this study.

1.2 Background

Several methods to measure high temperature in harsh environments are currently available including conventional thermocouple, resistance thermometry, SiAlCN ceramics, wireless thermocouple connector systems, surface acoustic wave (SAW), and radio frequency (RF) powered induction-capacitance (LC) temperature sensor [3,6-8]. Thermocouples are very

sensitive and very limited in terms of service life and accuracy. Thermocouples in harsh environments tend to get corroded due to corrosive chemicals, which can limit its operational life [2]. Conventional thermocouples are composed of two wires of different material that meet at two ends, the different materials develop a voltage difference between them and is transferred to the other end where the temperature is read. When exposed to high temperature, the metal of the wires can get corroded and malfunction usually occurs [2]. Furthermore, conventional thermocouples cannot be used in every application, sometimes wiring is not desired in the energy system where wire can obstruct the closure of a sealed environment. Resistance thermometry uses the temperature dependence of electrical resistance of conductive material to measure temperature between -260 °C and 962 °C. Theoretically any conducting material can be used as a resistive temperature sensor but the limitation for selection of materials are considered in terms of temperature resistance, cost and resistance to oxidation [9]. Limitations of existing intrusive temperature measurement methods emphasize the strong need for high temperature sensing in harsh environments [2,10,11].

A ceramic sensor made out of polymer-derived SiAlCN ceramics (PDCs) has been experimented for high temperature wireless sensing [7]. In this study, a temperature sensor using PDC and an embedded system were tested. PDC sensors are resistive sensors that transmit their signals through a WiFi port on the embedded circuit. The cost for the manufacturing and deplorability to the public for real life applications is high for this application. The total fabrication process for a single PDC ceramic sensor is approximately fifty-two hours, and there is complexity with keeping the purity of the sample if the fabrication is not carried out in high-purity nitrogen to avoid as much contamination as possible. One major disadvantage would be the Wi-Fi port and hotspot since signal can be easily lost. The

company Omega has developed a wireless thermocouple connector system that transmits radio frequency signals, which transfers the thermocouple's information to a host receiver [8]. It has a universal adaptor which allows for different connectivity types of thermocouples. According to Omega, the system is powered by a battery that lasts 1.5 years at a rate of 1 sample per minute at room temperature. However, if temperature needs to be monitored at a much higher frequency, then the battery would need to be replaced much more often. In this setup, Omega's wireless temperature sensor is a particularly expensive system because all the necessary components to function are sold separately which include: the thermocouple connector, transmitter, receiver, and battery replacements.

RF powered LC temperature sensor was developed by the department of mechanical engineering at the University of Puerto Rico [3]. A passive LC resonant telemetry scheme, which relies on a frequency output that communicates a sensor made of a high-K temperature sensitive ceramic material with a reader in order to measure the temperature with no physical contact. An electrical capacitor is the design principle of the temperature sensor. The capacitor acts as the temperature sensor since its dielectric constant variates linearly with temperature, therefore capacitor's capacitance changes according to its exposed temperature. Oscillating current on the reader's antenna generates magnetic field which can be transferred to the sensor's antenna, an alternating voltage is induced in the sensor at a constant frequency. Frequency changes with environment's temperature and therefore antenna from the reader picks up the varying frequency signal from the sensor. However, the outputting frequency from sensor can be easily disrupted by electromagnetic interference (EMI). EMI can alter the LC circuit by electromagnetic induction causing an inaccurate temperature measurement.