Thermoelectric Powered High Temperature Wireless Sensing*

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Abstract

This study describes use of a thermoelectric power converter to transform waste heat into electrical energy to power an RF receiver and transmitter, for use in harsh environment wireless temperature sensing and telemetry. The sensing and transmitting module employs a DS-1820 low power digital temperature sensor to perform temperature to voltage conversion, an ATX-34 RF transmitter, an ARX-34 RF receiver module, and a PIC16f84A microcontroller to synchronize data communication between them. The unit has been tested in a laboratory environment, and promising results have been obtained for an actual automotive wireless under hood temperature sensing and telemetry implementation.

Key words: Thermoelectric Generator, Buck-Boost Converter, Wireless Sensing, RF Receiver and Transmitter, Waste Heat Treatment, High Temperature

1. Introduction

Historically, most high temperature sensing has been performed using thermocouples. Disadvantages of this approach include a need to incorporate high temperature cabling into designs, which in turn adds complexity to system wiring. Wireless sensing has the potential to eliminate many such disadvantages in industrial or automotive under hood temperature sensing and telemetry applications. Techniques for wireless temperature sensing that have been explored to date include Infrared Thermal [1], and Laser [2] approaches, however all of these require an unobstructed line of sight between the sensing unit and the object whose temperature is being measured [3]. This line of sight requirement is the primary obstacle to successful application of those techniques to automotive under hood wireless temperature sensing. The obstacle can be overcome by using an RF transmitter and receiver to wirelessly transmit temperature data. Each side of such a communication link requires access to a DC power supply. Providing this power to the receiver side is easy since typically it does not reside in a harsh environment, and in fact usually resides in a location in which it can share a power source with other instrumentation. There exist precedents for powering data transmitters with batteries, solar cells, fossil fuel powered generators, and even (as in the case of Radio Frequency Identification applications) a brief electrical current induced by an externally generated magnetic pulse, when for whatever reason access to a more conventional power source is unavailable.

The purpose of this study is to explore yet another alternative, namely, the use of a Thermoelectric Generator (TEG) to supply power to the data sensing and RF transmission component of the system. Such an approach may be particularly well suited to applications in which the sensor resides in a high temperature environment that may adversely impact

batteries, or in a hazardous or difficult to access location for which availability of a self sufficient sensor and transmitter module that can operate indefinitely, yields periodic maintenance expenditure related savings that outweigh the costs of manufacturing and initial installation. This study is a proof of concept, focused on ensuring that unanticipated obstacles do not prevent construction, calibration and use of a TEG powered high temperature sensing and RF data transmission unit, in a controlled high temperature laboratory setting that is free of unusual RF noise, humidity, vibration, or other environmental anomalies. This includes confirming that neither the electrical nor thermal characteristics of the TEG device itself adversely impact the calibration or operation of the temperature measurement circuitry. This is accomplished by confirming that temperature data acquired using a calibrated TEG powered circuit constructed from off the shelf components is equivalent to data acquired by conventional means. Future studies may explore impacts of other aspects of environmental harshness on performance differences between TEG powered and thermocouple based systems.

The amount of power produced by a TEG device, depends on the magnitude of the temperature difference between two of its sides, which are henceforth referred to as the “hot side” and the “cold side”. If the hot side is mounted on a hot surface whose temperature we would like to measure, and the cold side is connected to a heat sink that is exposed to open air, the amount of energy produced by the TEG device suffices to power the transmitter. A block diagram illustrating this architecture is presented in Fig 1.

Fig. 1. Thermoelectric Powered Wireless High Temperature Sensing and Telemetry

2. TEG Component of Proof of Concept System

2.1 Theory of Thermoelectric Power Generation

The thermoelectric effect was first discovered in 1822 by Thomas Joann Seebeck (1770-1831), who observed electric current flow when one junction of two dissimilar metals, joined at two places, was heated while the other junction was kept at a lower temperature [4]. A typical multi couple thermoelectric power module is presented schematically in Fig 2 which depicts p-type and n-type semiconductor thermo elements connected in series by highly conductive metal strips to form a thermocouple. According to an improved theoretical model which takes into account thermal and electrical contact resistance, the output voltage

V_o , current I_o , and power P_o when the module is operated with a matched load, are given by equations [5].

Fig. 2. Principle schematic of a single thermoelectric-couple

$$V_o = \frac{\alpha N(T_h - T_c)}{1 + 2rL_c / L}, \quad 1$$

$$I_o = \frac{\alpha A(T_h - T_c)}{2\rho(L + n)(1 + 2rL_c / L)}, \quad 2$$

$$P_o = \frac{\alpha^2}{2\rho} \frac{NA}{(L + n)(1 + 2rL_c / L)} (T_h - T_c)^2, \quad 3$$

where $n=2\rho c/\rho$, $r=\lambda/\lambda_c$, α is the thermoelectric material's Seebeck co-efficient (V/K), ρ is electrical resistivity ($\Omega\text{-cm}$), ρc is electrical contact resistivity, N is the number of thermo elements (mm^2), L 's the length of the thermo element (mm), L_c 's the thickness of the contact layer (mm), T_h is the temperature at the hot side ($^{\circ}\text{C}$), T_c is the temperature of the cold side ($^{\circ}\text{C}$), λ is the thermal conductivity of the contact layer [6]. Contemporary TEG devices are manufactured using techniques similar to those pertaining to the manufacturing of semiconductors [12].

2.2 Choice of Thermoelectric Power Generation module

The TEG module that we chose to incorporate into our study is the QUICK-OHM Küpper & Co. GmbH *TMG-450-0.8-1.0*. Its operating properties for hot side temperature equal to 175°C and cold side temperature equal to 50°C are presented in Table 1. Under those conditions maximum efficiency of electric power generation is approximately 3%. That efficiency is computed using the formula $W_{\text{load}}/Q_{\text{hot}}$ where W_{load} is output power (in Watts), and Q_{hot} is the heat flow (in Watts) through the module.

Table 1 Specification of the *TMG-450-0.8-1.0*.

Part number	TMG-450-0.8-1.0
Dimensions: Cold side	54.4 x 57.0 x 3.4mm.
Dimensions: Hot side	54.4 x 54.4 x 3.4mm.
Open circuit voltage	21V @125 °C temperature difference.
Internal resistance	21.5 Ω
Match load output-voltage	12V @ 28 Ω Load Resister.
Match load output-current	416mA.
Match load output-power	5 W.
Module thermal conductance	1.45W/°C.
Heat flux across of the module	159.5Watts.
Heat flux density of the module	5.46Watts/cm ² .

2.3 Finding the Electrical Characteristic of the *TMG-450-0.8-1.0* module

A temperature controlled electric heater was used to supply heat to the hot side of a *TMG-450-0.8-1.0* thermoelectric generator module. A Constant Temperature Bath was used to keep the cold side of that module at a constant temperature of approximately 25°C (see Fig. 3). The electrical characteristics of the *TMG-450-0.8-1.0* were measured while the hot side temperature was gradually increased from approximately 50°C to approximately 225°C. The module's output voltage was measured with a load (equal to the TEG module's internal resistance which in turn results in max power transfer out of the module: R_L 21.5 Ω), and without a load. All of the captured data is presented in Table 2, and plotted in Fig. 4-5.

Fig. 3. Experimental test setup for electrical characteristic of the *TMG-450-0.8-1.0*.

Table 2 Experimental Data for the *TMG-450-0.8-1.0*.

T_h °C	T_c °C	V_{OC} Volt No Load	V_{Out} Volt Load $R=21.5\Omega$	T_h-T_c °C	I_L Load Current Amperes
47.0	25.0	2.68	1.28	22.0	0.059535
58.5	25.5	3.86	2.04	33.0	0.094884
66.1	24.0	5.23	2.53	42.1	0.117674
75.5	25.2	6.36	3.01	50.3	0.140000
85.0	24.6	8.13	3.56	60.4	0.165581
97.1	25.0	9.14	4.24	72.1	0.197209
103.2	24.0	9.82	4.61	79.2	0.214419
116.5	25.1	10.87	5.29	91.4	0.246047
124.7	25.6	11.61	5.76	99.1	0.267907
135.9	24.9	12.93	6.23	111.0	0.289767
144.8	24.6	13.35	6.57	120.2	0.305581
153.1	25.7	14.39	6.80	127.4	0.316279
159.1	25.0	15.20	7.06	134.1	0.328372
169.8	25.0	15.95	7.54	144.8	0.350698
179.5	25.5	16.76	7.78	154.0	0.361860
194.0	25.4	17.03	8.14	168.6	0.378605
204.4	25.2	17.64	8.41	179.2	0.391163
211.2	24.2	18.3	8.61	187.0	0.400465
218.2	25.0	18.76	8.71	193.2	0.405116
225.2	25.2	19.03	8.97	200.0	0.417209
Avg $T_c = 24.985$ °C

Fig. 4. TEG Output Voltage versus Hot Side Temperature (Cold Side@25°C) with Load and No Load.

Fig. 5. Fitting Curve to the Real TEG Data to find out Hot Side Temperature out of TEG Output Voltage.

The MATLAB Curve Fitting tool was used to fit the TEG Data to a quadratic equation presented in Table 3. In applications for which the cold side temperature is held constant it is not necessary to incorporate a high temperature sensor into the system design, since the high side temperature can be calculated using PIC 16F84A. If the cold side temperature is not constant, as is the case for many applications, a high temperature sensor is an inevitable component of most implementations. We have chosen to incorporate a digital temperature sensor into the design that is explored by this paper.

Table 3 Quadratic equation constant and fitting parameters.

Linear model Poly2: $f(x) = p1 \cdot x^2 + p2 \cdot x + p3$			
Coefficients (with 95% confidence bounds):			
p1 = -0.0002707 (-0.0002892, -0.0002522)			
p2 = 0.167 (0.1619, 0.1722)			
p3 = -4.818 (-5.143, -4.494)			
Goodness of fit:			
SSE: 0.1756	R ² : 0.9997	Adjusted R ² : 0.9996	RMSE: 0.1016

3. Data Sensing and Communication Components of Proof of Concept System

Brief descriptions of components other than the TEG module, that we incorporated into the design of our proof of concept system, are presented in the subsections below.

3.1 DC-DC Switched Mode Buck-Boost Non-Inverting Regulator in an IC Package

The *max641 commercial* Maxim IC is a buck-boost non-inverting fixed (+5V) voltage regulator [7]. It's input DC voltage may vary between +2 to 16.5 Volts and its output voltage will be equal to DC +5 Volts. It's maximum current output (when using an internal MOSFET) is equal to 325mA. Using an external MOSFET this can be increased to 2 Amps.

3.2 Temperature Sensor

The DS18S20 Digital temperature sensor provides 9-bit Centigrade temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points. The DS18S20 communicates over a 1-wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. It has an operating temperature range of -55°C to $+125^{\circ}\text{C}$ and is accurate to $\pm 0.5^{\circ}\text{C}$ over the range of -10°C to $+85^{\circ}\text{C}$. In addition, the DS18S20 can derive power directly from the data line, eliminating the need for an external power supply. Each DS18S20 has a unique 64-bit serial code, which allows multiple DS18S20s to function on the same 1-wire bus; thus, it is simple to use one microprocessor to control many DS18S20s distributed over a large area. Applications that can benefit from this feature include HVAC environmental controls, temperature monitoring systems inside buildings, equipment or machinery, and process monitoring and control systems [8].

3.3 ASK Receiver and Transmitter

The ATX-34 UHF ASK data transmitter was developed to cover a band plan ERC Recommendation on Short Range Devices in the 434MHz Industrial, Scientific, and Medical band. It was designed for printed circuit board mounting. A simple wire can be soldered to its antenna input pin or an antenna can be printed on a printed circuit board. Module applications include remote control systems, telemetry systems, social alarm systems, security alarm systems and paging systems [9].

This compact RF receiver module is suitable for remote control or telemetry applications. The double sided circuit board is pre-populated with surface mount devices and is tuned to 433MHz.

3.4 PIC16f84A 8-bit Microcontroller

The PIC16f84A 8-bit Microcontroller is a classic PIC micro device. It includes flash program memory, RAM data memory and a Microchip RISC instruction set comprised of 35 mostly single cycle execution instructions. It conforms to a Harvard Architecture with separate 14-bit program bus and 8-bit data bus for fast operation [10]. PIC16F84 perfectly fits many uses, from automotive industries and controlling home appliances to industrial instruments, remote sensors, electrical door locks and safety devices. It is also ideal for smart cards as well as for battery supplied devices because of its low consumption. EEPROM memory makes it easier to apply microcontrollers to devices where permanent storage of various parameters is needed (codes for transmitters, motor speed, receiver frequencies, etc.). Low cost, low consumption, easy handling and flexibility make PIC16F84 applicable even in areas where microcontrollers had not previously been considered (example: timer functions, interface replacement in larger systems, coprocessor applications, etc.). In System Programmability of this chip (along with using only two pins in data transfer) makes possible the flexibility of a product, after assembling and testing have been completed. This capability can be used to create assembly-line production, to store calibration data available only after final testing, or it can be used to improve programs on finished products.

4. Architecture and Performance of Proof of Concept System

Descriptions of the architecture and performance of our proof of concept system, are presented in the sub-sections below.

4.1 High Temperature Sensor and Wireless Transmitter Module

Our high temperature sensor and wireless transmitter module is described below. A block diagram and photo are presented in Fig. 6. When the temperature difference between the hot and cold sides of the thermoelectric module reaches 20°C, it creates V_{TEG} approximately equal to 2.74 Volts (Table 3) . This is enough to power up the high temperature sensor and transmitter module. The module starts reading data from the DS1820S digital temperature sensor and this data directly drives the PIC16F84A microcontroller where an embedded program (PIC Basic [11]) routes the data to the ATX-34 RF transmitter which in turn uses the Amplitude Shift Keying modulation technique to broadcast the data through the antenna into the surrounding space.

Fig. 6. High Temperature Wireless Sensing and Transmitter Module Block Diagram and Photo

The standard ASK data protocol used by the ATX-34 requires communication of preamble and synchronization pulses prior to communication of data values. The preamble and synchronization pulses are used to establish hardware and software synchronization respectively, between the transmitter and receiver modules [12].

4.2 High Temperature Wireless Sensing Receiver Module

Our high temperature data receiver module is described below. An ATX-34 module transmits data to an ARX-34 RF module at a rate of 2400 bps, using the 434 MHz band. The digital output of the RF-receiver module is connected to a 16F84A microcontroller on which a PIC Basic program manages the digital temperature data and converts it to analog outputs needed to drive a 2x16 Liquid Crystal Display. Temperatures are presented by that display in human readable form. Module power up and operation up is maintained by a 7805 linear regulator that processes the output of a power supply comprised of a 9 Volt cubical battery. A block diagram and a photograph of the High Temperature Wireless Sensing Receiver Module are presented in Fig. 7.

Fig. 7. High Temperature Wireless Sensing Receiver Module Block Diagram and Photo

4.3 Experimental Test Setup, Measurement and Results

Experimental test setup includes a hot plate, thermoelectric generator module, buck-boost regulator, RF transmitter and receiver, hot and cold side temperature meters that rely on thermocouples, TEG and regulator output voltage meter for both temperature and voltage monitoring respectively. The hot plate temperature is increased gradually and the hot and cold side temperatures, TEG module output, buck-boost regulator output voltage, and hot side temperature reported wirelessly are all monitored and recorded. The resulting data is summarized in Table 4 A plot of the difference ΔT ($T_h - T_c$) between temperature measured using a thermocouple, and the temperature measured using our wireless apparatus is presented in Fig. 8.

Table 4 High Temperature Measurement Range between 50-125 °C

Tcold °C	Thot Direct °C	Thot Wireless °C	Vteg Volt	Vreg Volt	ΔT (T_h Direct T_c) °C
33.1	53.2	54	2.74	2.49	20.1
33.6	57.6	58	3.44	3.33	24
35.3	64.5	64	3.59	3.61	29.2
38.8	71.7	71	3.75	4.62	32.9
42.4	82.8	82	5.96	4.99	40.4
43	88.7	88	6.4	4.99	45.7
44.8	92.8	92	6.93	5.00	48
46.9	101.5	101	7.51	5.00	54.6
48.3	105.7	106	7.69	5.00	57.4
49.6	112.2	112	8.58	5.00	62.6

Fig. 8. ΔT ($T_h - T_c$) versus both direct and wireless measured temperature

The experimental data shows us the wireless temperature sensing module starts reading temperature data when ΔT ($T_h - T_c$) reaches a temperature difference of 20°C. At this point VTEG reaches 2.74 Volts and buck-boost regulator output reaches 2.49 Volts. At this point high temperature sensing and transmitting module starts to work properly. Comparing wireless and direct temperature measurement there is a slight gap between both measurements even though both sensors, namely the thermocouple and the DS18S20, are located next to each other on the hot side of the TEG module. This slight difference can be tolerated in most high temperature measurement systems. The described wireless

temperature sensing system is capable of measuring temperatures that lie between 50 and 125 °C. Maximum temperature readings greater than 125 °C could be obtained using temperature sensors other than the DS12S20, which can only read up to 125 °C. This is a limitation of the sensor not the wireless sensing and transmitting module. In order to produce expected results systems like the one we described need to be calibrated for operation in their intended environments. Direct measurement of temperatures was carried out using conventional components with well-documented reliability characteristics. We would feel obligated to analyze and report those characteristics if reporting precise absolute temperatures was one of this study's priorities. Our goal however is slightly different: It is to verify that the temperature measurements produced by the TEG powered circuit are equivalent to those obtained using conventional alternatives, and for that purpose it suffices to note that a) we carried out a large number of temperature measurements, both using the TEG powered circuit, and using conventional measurement; b) there was very close agreement between corresponding elements of those two data sets; c) because of the large number and varied magnitudes of the obtained temperature measurements, the probability that their agreement is due to coincidence, is extremely low. Hence we are confident based on purely statistical arguments, that irrespective of the precision of absolute values of temperature measurements, the performance of our TEG powered temperature data sensing and transmission circuit, is equivalent to that of the conventional alternative that we examined.

5. Conclusion and Future Work

This study proves that waste heat can be transformed using thermoelectric generation materials into a sufficient amount of power to drive a microelectronic circuit that reliably performs a useful high temperature sensing and RF data transmission task. There exist many wireless high temperature sensing techniques, including those that rely on infrared, pyrometers, and thermal imaging; however, they all require an unobstructed line of sight between the sensor and the location at which temperature is being measured. The advantage of the wireless temperature sensing approach presented in this study is that since RF signals can travel through many types of objects, no unobstructed line of sight is required between the temperature sensor and equipment that needs to use the temperature readings produced by that sensor. The techniques described by this study could easily be applied to automotive radiator or engine temperature monitoring. Such an implementation would eliminate the need for high temperature cabling, and an under hood to instrument panel hole. The example implementation we produced could easily be modified, to allow it to participate in a wireless control area network. It is also not inconceivable that the manufacturing costs, installation costs, reliabilities, and maintenance costs pertaining to circuits like the one we described could be made arbitrarily attractive, and superior to those pertaining to implementations that rely on high temperature cabling, through a combination of miniaturization and economics of scale. For example, thermoelectric P-N bars and supporting circuitry equivalent to that which we described could be manufactured on a substrate to produce a small low cost monolithic high temperature wireless sensing integrated circuit that does not require a power supply. For specialized applications in which large amounts of RF background noise, security, humidity and other environmental factors are an issue, a ruggedized version equipped with sophisticated cryptography, data transmission error detection and correction up to and including data packet re-transmission, would be no less feasible than is currently the case for existing applications like GPS and wireless computer networking. While it is true that such circuits consume more power than wired alternatives, the power being consumed when using TEG implementations is waste heat and hence does not adversely affect the environmental impact of devices which rely on them.

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