

Distributed Sensor-less Self-powered System for Measurement of Temperature Difference

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Abstract- The paper deals with a theoretical analysis and a feasibility study on a method for measurement of temperature difference between two objects. An idea of distributed and self-powered system for indirect measurement of ΔT is presented. It relies on two nodes consisting of thermoelectric modules (TEMs), instead of dedicated temperature sensors. Therefore, the essence of the method requires a wireless link to exchange data between two points (not necessarily to transfer measured data to a hub). Due to the Seebeck effect, the thermoelectric devices respond with output voltages proportional to temperature gradients. Moreover, in the presented concept the TEMs play also roles of local thermogenerators powering radio transceivers and conditioning electronic circuits necessary to read, process, and send the data. The presented solution can be applied, for example, to automatic control, telemetry systems and heat metering.

I. Introduction

Distributed measurement systems are commonly used today as the wireless technology is getting more and more popular. They are essential part of industrial automation, assuring quality of production, increased reliability and safety [1]. However, the necessity of supplying electrical power to each sensor node, either by wire or by battery, is a real nightmare to designers and service teams. Maintenance of hundreds miles of electrical cables or periodic battery replacement require a large amount of work; it is ineffective and lower the overall reliability of the monitoring system. Lack of independent and reliable electric power sources hinders to some extent proliferation of telemetry networks. To counteract this problem a new research domain – energy harvesting - is developing very rapidly recently [2], [3]. It focuses on scavenging small amounts of “free” energy (light, heat, vibrations, electromagnetic background) and converting into electricity [4], [5].

For some years our team has investigated autonomous sources of energy, intrinsic to the central heating systems as well as to waste industrial heat, that would be suitable for supplying remote sensor nodes [6], [7]. We tested the hypothesis that by extracting and converting thermal energy from central heating systems we could obtain electrical energy that would be sufficient to supplying telemetry networks. We aimed to find a substitute of independent self-powered devices characterized by infinite lifetime that could revolutionize future telemetry market, and we expected to prove that small amounts of waste heat can be successfully and efficiently converted into electricity.

The objective of this work was to carry out a study on a concept of self-powering system that at the same time could measure temperature difference between two objects, and would not require dedicated temperature sensors. The presented solution can be regarded as a part of a global trend, that is consistent with the Internet of Things paradigm applied to measurement systems. It foresees that in the near future most of the different kinds of entities will be independent and autonomous in terms of electrical power supply as well as connectivity [8].

II. The concept of the method

The presented concept relies on using two completely autonomous nodes consisting of thermoelectric generators, conditioning electronic circuits for signal processing, and wireless transceivers. At the same time the thermoelectric modules play two very important roles. Firstly, they convert available heat into electrical energy required for powering electronic system. Secondly, they take over the function of temperature sensors.

A. A combined thermoelectric generator and a gradient temperature sensor

A thermoelectric module is a solid state element consisting of many thermocouples made of bismuth telluride (Bi_2Te_3) p-n junctions, joined together by copper straps, and sandwiched between two alumina (Al_2O_3) plates (Fig. 1).

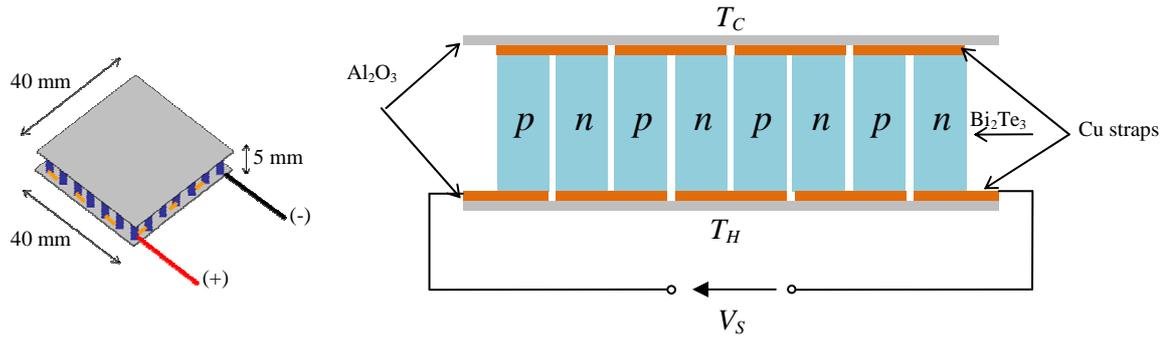


Figure 1. Thermoelectric module and its cross section

The p-n pellets are connected electrically in series, and thermally in parallel. Thus, when the TEM is subjected to a temperature gradient $T_H - T_C$ across its plates, it will deliver a voltage V_S that is equal total Seebeck voltages generated by all small thermocouples (1).

$$V_S = \alpha(T_H - T_C) \quad (1)$$

where: α – Seebeck coefficient.

When the output V_S is connected to an electrical load, then the TEM is generating electrical power. On the other hand, the TEM can be regarded to some extent as a good temperature sensor because the Seebeck voltage is proportional to a temperature gradient.

B. A model of heat conduction through a layered structure

A single node consists of a block of good heat conducting material (copper or aluminum), that is next attached to a thermoelectric module, which is finally fixed to a heat sink exposed to ambient temperature T_a . Figure 2 shows a detailed layered cross section of two identical nodes working in the same ambient conditions, but applied to different objects, at temperature T_1 and T_2 , respectively.

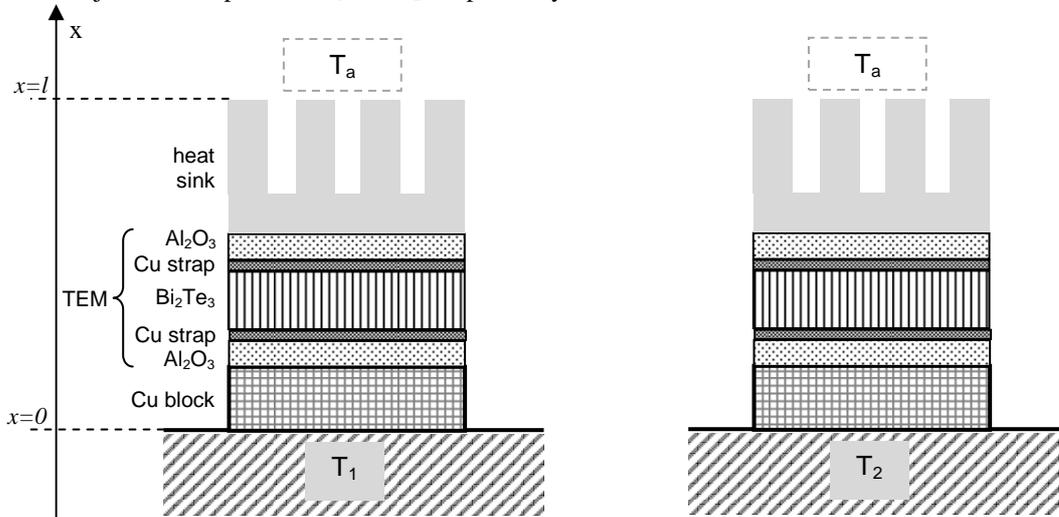


Figure 2. Cross section of the two thermogenerator systems attached to objects at temperatures T_1 and T_2

When the thickness of the individual layers is much smaller than the surface dimensions, then the lateral sides of the thermogenerators can be regarded as adiabatic ones (2). A temperature distribution along the x axis at steady state can be obtained by solving the equation (3):

$$\frac{\partial T(x, y, z)}{\partial y} = 0, \quad \frac{\partial T(x, y, z)}{\partial z} = 0 \quad (2)$$

$$\lambda \nabla^2 T(x) = 0 \quad (3)$$

where: λ – thermal conductivity coefficient.

The boundary conditions for both nodes can be expressed as in (4), and the heat conduction between individual layers as in (5) [9], [10].

$$\text{node_1: } T(x)|_{x=0} = T_1 \quad \text{node_2: } T(x)|_{x=0} = T_2 \quad \text{both nodes: } T(x)|_{x=l} = T_a \quad (4)$$

$$\lambda_{layer_n} \frac{dT_{layer_n}(x)}{dx} \Big|_{x=l_n} = \lambda_{layer_n+1} \frac{dT_{layer_n+1}(x)}{dx} \Big|_{x=l_{n+1}}, \quad T_{layer_n}(x) \Big|_{x=l_n} = T_{layer_n+1}(x) \Big|_{x=l_n} \quad (5)$$

C. An electrothermal model of the system

Solution of the equation (3) with boundary condition (4)-(5) gives a heat flux Θ in the first node that is expressed by (6). The heat conduction phenomena in the nodes can be represented by an equivalent electrothermal circuit that is shown in Fig. 3.

$$\Theta_1 = \frac{T_1 - T_a}{\sum_{n=1}^N \frac{l_n}{S_n \lambda_n}} = \frac{T_1 - T_a}{\sum_{n=1}^N R_{th_n}}, \quad \Theta_2 = \frac{T_2 - T_a}{\sum_{n=1}^N \frac{l_n}{S_n \lambda_n}} = \frac{T_2 - T_a}{\sum_{n=1}^N R_{th_n}} \quad (6)$$

where: S_n – surface area of the individual layers, R_{th_n} – thermal resistance of the individual layers.

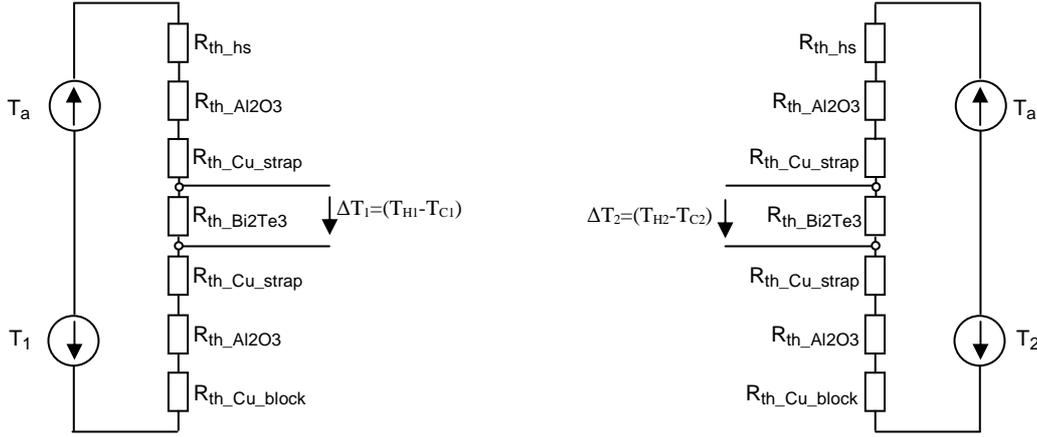


Figure 3. Electrothermal models of two thermogenerator nodes

The temperature gradients across the TEMs and the corresponding Seebeck voltages can be expressed as in (7) and (8) respectively.

$$\Delta T_1 = (T_{H1} - T_{C1}) = \Theta_1 \cdot R_{th_Bi2Te} = \frac{(T_1 - T_a) \cdot R_{th_Bi2Te3}}{\sum_{n=1}^N R_{th_n}}, \quad \Delta T_2 = (T_{H2} - T_{C2}) = \Theta_2 \cdot R_{th_Bi2Te} = \frac{(T_2 - T_a) \cdot R_{th_Bi2Te3}}{\sum_{n=1}^N R_{th_n}} \quad (7)$$

$$V_{S1} = \alpha \cdot \Delta T_1, \quad V_2 = \alpha \cdot \Delta T_2 \quad (8)$$

The voltage ΔV_S between the two voltages V_{S1} and V_{S2} is proportional directly to the temperature difference $T_1 - T_2$ of the two objects (9). In fact, only the information regarding V_{S1} and V_{S2} has to be exchanged between these two nodes to perform appropriate measurement.

$$\Delta V_S = V_{S1} - V_{S2} = \alpha (T_1 - T_2) \cdot \frac{R_{th_Bi2Te3}}{\sum_{n=1}^N R_{th_n}} \quad (9)$$

III. Measurements and results

A prototype thermogenerator-sensor node was designed and subjected to testing by means of a special laboratory stand where temperature of the object T_0 could be controlled in the temperature range from 25°C to 80°C.

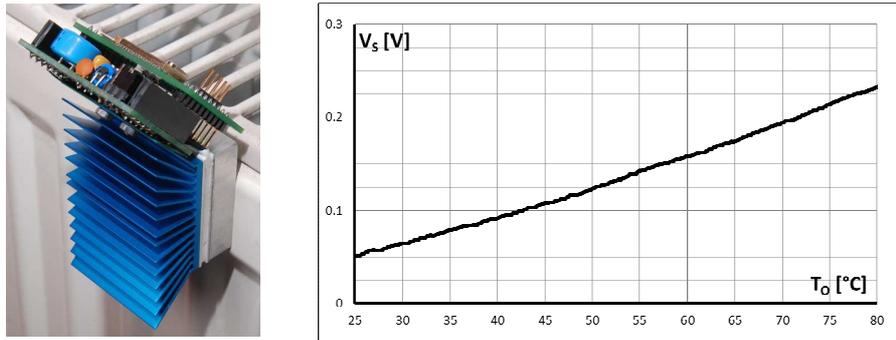


Figure 4. A prototype thermogenerator-sensor node (left) and the Seebeck voltage vs. T_0 (right)

The duty cycle of each node consists of two modes: the power generation, and the Seebeck voltage sensing at open circuit (no power generation). The time ratio between these modes is a trade-off between measurements frequency and the required energy for transmission. The available power at matched load 3Ω was in the range of a few mW up to over a dozen mW, and it was sufficient to supply the electronic circuit and the transceiver unit. In Fig. 5, a linear relation between temperatures T_O and T_C is shown, as well as the temperature gradient across the TEM against T_O .

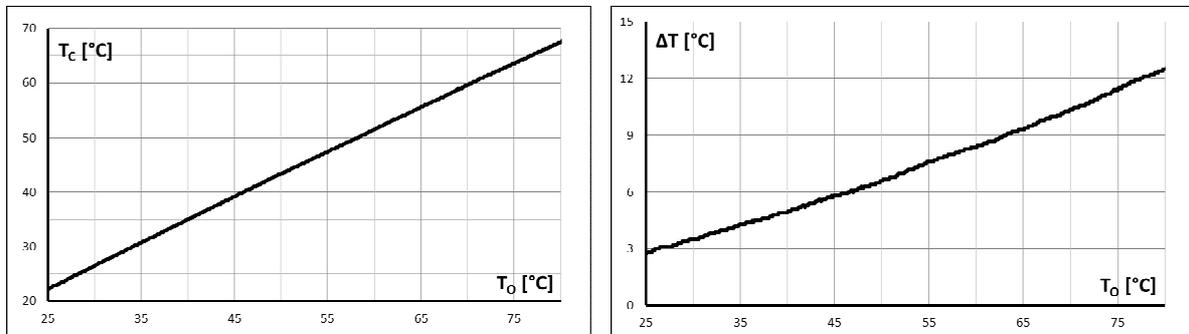


Figure 5. Linear relation between temperatures T_O and T_C (left), and the temperature gradient against temperature of the object (right)

IV. Conclusions

The proposed prototype thermogenerator-sensor node makes possible to measure temperature difference of two independent objects, provided that they are placed in the same ambient conditions. There are many cases where the temperature gradient is essential and not the absolute value of the temperature. One of the examples is a heat meter that calculates the heat consumption, based of heating medium flow rate and the temperature difference between input as well as output of the heating loop. The advantage of the presented solution is the combined autonomous power supply and the temperature converter.

The application of the method requires a combination of twin thermogenerators linked wirelessly. Such telemetry systems can provide data about operation status of the heating installations, they can warn in advance about possible failure to prevent excessive heat energy losses or system damage.

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