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A Concept of a Self-Powering Heat Meter

***Abstract**. In the paper a concept and a study of a self-powering solution for heat energy consumption measurement in home or industrial heating systems is presented. The batteryless heat meter, equipped with a wireless transceiver could constitute a long life completely autonomous device that would not need any servicing nor power sources replacement. The proposed thermoelectric generator attached to a heat source can provide single miliwatts of power when the temperature difference exceeds a few grades.*

***Streszczenie.** W artykule przedstawiono koncepcję i studium rozwiązania samo-zasilającego się licznika energii cieplnej dla systemu ogrzewania mieszkań i/lub powierzchni przemysłowych. Miernik energii cieplnej pracuje bez baterii i wyposażony jest w bezprzewodowy system nadawczo-odbiorczy system, który może pracować dostatecznie długo jako system autonomiczny nie wymagający serwisowania czy wymiany źródeł zasilających. Dołączony do źródła ciepła generator termoelektryczny może dostarczać mocy rzędu kilku miliwatów gdy różnica temperatur na grzejniku przekracza kilka stopni Celsjusza (**Koncepcja samo-zasilającego się licznika energii cieplnej**).*

Keywords: ambient energy harvesters, heat meters, self-powering devices, thermoelectric generators.
Słowa kluczowe: ambient energy harverters, liczniki energii cieplnej, urządzenia samozasilające się, generatory termoelektryczne

Introduction

Optimization of thermal energy utilization is one of the most important issues in times of increasing costs of energy production. On the other hand, the more and more restrictive environmental regulations force the end users as well as heat energy providers to pay more attention to power consumption and accurate heat flow metering. With the very fast development of wireless technology during the last few decades, it is now possible to constitute distributed telemetry systems consisting of many nodes performing simple measuring and calculation tasks [1], [2], [3]. Wireless heat flow controlling systems can be deployed rather quickly and not in a very intrusive way. Central heating installations in real estate sector as well as industrial processes benefit especially from an opportunity of more flexible arrangements of metering equipment.

Recent advances in microelectronic industry, manifesting in ultra low voltage operation and extremely low power consumption, have made another breakthrough and contributed to emerging very fascinating applications of ambient energy harvesting technology. The environmental energy scavenging is fulfilling the paradigm of completely autonomous systems that do not need any cabling, whether to provide data transmission or electric energy. Very small pieces of ambient energy can be collected from the ambient sources, such as: light, heat, vibrations, electromagnetic background, and next converted by the electronic system itself to electricity [4], [5], [6], [7].

In the paper we combine low power techniques and energy harvesting methods to show a new way of heat flow metering in central heating systems. The system configuration consists of two self-powering wireless nodes that can provide sufficient power to perform temperature gradient measurement and heat flow metering in order to estimate heat energy consumption. In the next following paragraph, a principle of heat metering is outlined. Next, the thermoelectric harvesting and energy conversion are described as well as some experimental measurements of available harvested electrical energy presented. At the end, a design and an arrangement of two self-powered sensor nodes are shown.

Principle of heat metering

The simplest, and at the same time not requiring electrical powering, an estimation method of heat energy consumption is the use of liquid heat evaporators. These devices are in the form of tubes filled with liquid and placed directly on the heat radiators. Because of temperature, the liquid is being gradually evaporated. The amount of evaporated liquid can be treated as an index of supplied thermal energy. Although the evaporation method is the cheapest, regarding the equipment and complexity, it does not allow for accurate quantification of heat energy consumption. Therefore, this method is rather suitable only for proportional allocation of costs of the energy supplied to many users.

More accurate methods of estimating heat consumption need application of some electronic devices powered by electricity. The first and less accurate one, uses only one temperature sensor attached to the radiator and a microcontroller unit. The proportional to the consumed heat energy indication is obtained by summing up the products of the temperature and the period of time for which the desired temperature is maintained.

The other method, the more precise one in turn, uses an additional sensor measuring room temperature. It allows the implementation of the algorithm which relies on summing up the product of the temperature gradient (between the radiator and ambient) and time periods.

The most accurate tool for determination of the heat flow energy, which is in fact a quantitative indicator of supplied energy from heating network, is a heat counter (or heat meter). Unfortunately, it also requires external power, which greatly complicates its use, because of the need for cyclic batteries replacement or providing access to the power grid. One can encounter some problems in more complex infrastructure, in which there are several independent circuits supplying thermal energy by means of heat transfer medium (most often the water). Difficulties appear due to installation costs as well as servicing and maintaining a huge number of counters/meters, not to mention issues concerning secure and reliable transmission and data exchange.

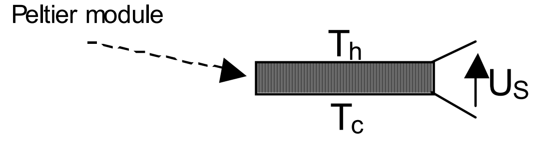

Fig.1. Thermoelectric module converting a temperature gradient to an electrical voltage

Typical heat meters use indications of two temperature sensors, measuring temperature gradient of the heating medium between an inlet and an outlet of the room.

Moreover, a transducer is used which provides electrical pulses with frequency that is proportional to the flow rate of the liquid. An embedded microcontroller reads the data from the sensors as well as from the transducer and performs calculation of the consumed heat Q according to the formula:

(1) $$Q = c_p \rho \sum V(T_1 - T_2)\Delta t$$

where: c_p – specific heat of the liquid medium [J/(kgK)]; ρ – density of the liquid medium [kg/m3]; V – flow rate of the liquid medium [m3/s]; $T1$ and $T2$ – temperatures at the inlet and the outlet of the room, respectively [K]ł
Δt – time period [s].

Specific heat and density are considered to be constant in the course of time, so the estimated heat is proportional to the sum of products: temperature difference and the frequency indicated by flow rate transducer.

The heat meter should be installed close to the inlet of the pipe supplying the heat energy to the room. The signals from temperature sensors and the flow sensor are transmitted by wire. The whole equipment is supplied by replaceable batteries or connected to the mains power grid.

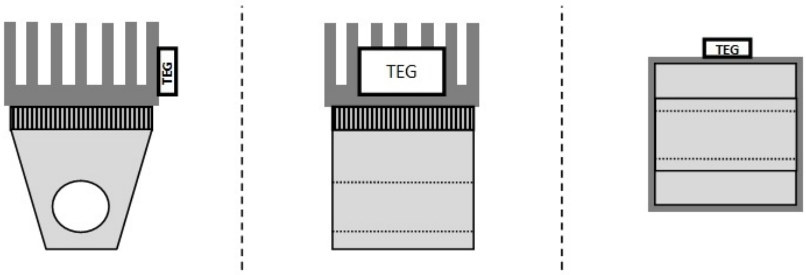

Fig. 2. Mechanical design of the thermoelectric generator dedicated to heat energy metering

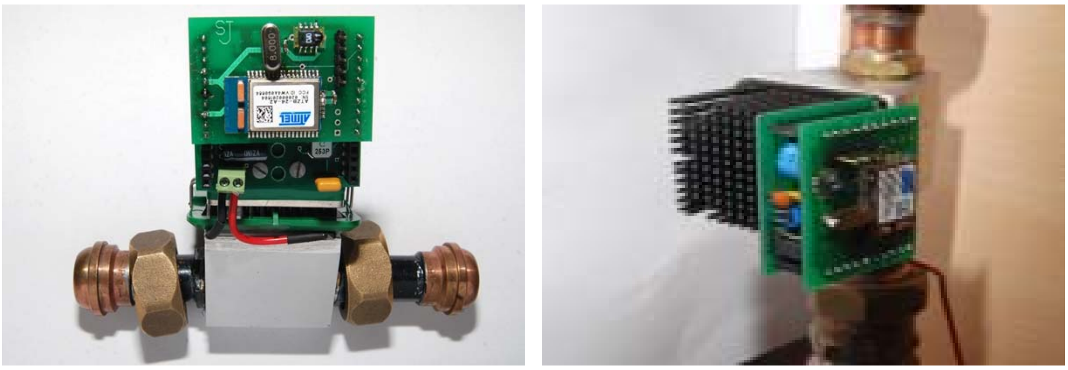

Fig. 3. A prototype thermoelectric generator and wireless sensor node

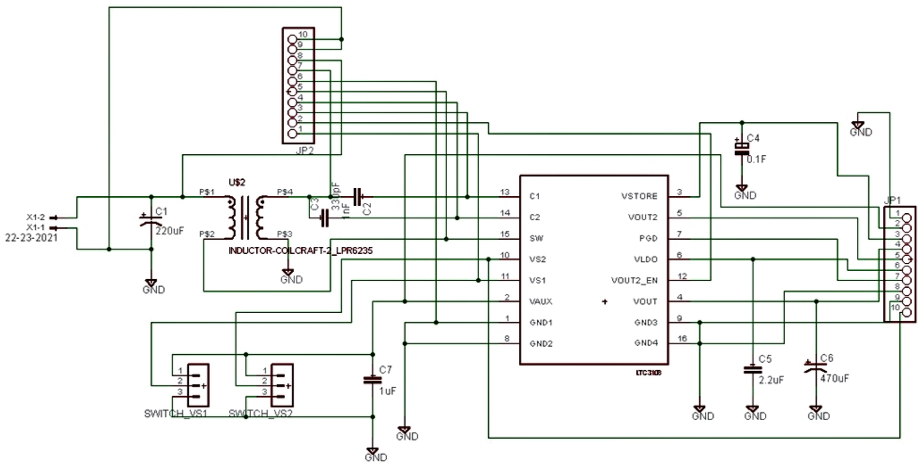

Fig. 4. Scheme of the TEG circuit

Thermoelectric harvesting and energy conversion

A thermogenerator is built of a Peltier module which is using the Seebeck effect to convert a temperature gradient (Th-Tc), existing at the both sides of the module, to a voltage US, according to the formula (2), (Fig. 1).

(2) $$U_S = \alpha(T_h - T_c)$$

where: α – Seebeck coefficient [V/K],
T_h – hot side temperature [K];
T_c – cold side temperature [K].

After closing the electrical circuit the Peltier module is becoming a source of energy, for instance for powering the heat meter elements. The obtained Seebeck voltage from the Peltier module is very low, therefore it has to be boosted and regulated to a level that is required by electronic circuits (microcontroller, sensors and transceivers).

The thermoelectric module equipped with boosting circuit needs at least 1° C of the temperature gradient to start powering the heat meter. The required temperature difference is achievable by affixing one side of the thermoelectric module to a copper or aluminium body, which is next attached directly to the heat source (pipe transporting hot water) with a good thermal contact. The other side of the thermoelectric module is attached to a small heat sink dissipating heat to the ambient. Figure 2 shows three different views on a mechanical design of the thermogenerator. In Figure 3, a prototype autonomous self-powering node is shown. It is equipped with optional microcontroller and transceiver unit which is responsible for reading data from sensors as well as for the calculation of energy consumption, and at the end for wireless data transmission. In addition to heat dissipation and lowering the temperature of the cold side of the Peltier module, the heatsink also acts as an assembly structure for electronic circuit TEG which comprises an ultra low voltage converter, a temporary storage of electrical energy and a power management module based on LTC3108 chip (Fig. 4).

The prototype of thermoelectric generator was subjected to testing by means of a laboratory stand imitating a real central heating installation. Temperature of the liquid medium was controlled from 20°C to 85°C. The next following graphs show obtained results at the matched load R_L of about 3.1 Ω. Figures 5 and 6 illustrate output voltage U of the thermogenerator against temperature of the hot side T_h and temperature gradient ΔT respectively.

The chart from Figure 7 shows the output power in relation to the temperature T_h of the heating medium. All the measured data proves that even in home conditions when the temperature of the radiators can reach up to 50°C, the Peltier module based generator is able to provide enough electrical power to supply some electronic circuits, including heat meter.

The modeling and simulations of the thermal energy harvesting processes that allow virtual estimation of available electrical power have been subject of our research work for many years [8]. Similarly, a wireless link supplied with harvested power was initially examined recently [9].

A new approach to heat metering

In the proposed new solution of a completely autonomous system for heat consumption measurement, a configuration consisting of two thermogenerators attached to the central heating system is used, as shown in Fig. 8.

Thermogenerators TEG1 - attached to the inlet of the heating system at a temperature $T1$, and TEG2 - fixed near the outlet at the temperature $T2$, play roles of thermal energy converters supplying electronic circuits that perform sensing, signal processing and transmission functions.

The idea of the proposed solution is to completely replace dedicated temperature sensors T1 and T2 required for the determination of thermal energy (1), by thermoegenerators TEG1 and TEG2 that at the idle state (no load) generate Seebeck voltages (2) which are proportional to the temperatures T1 and T2 respectively.

Assuming that the both thermogenerators are identical and working at the same ambient temperature Ta, one can derive a formula (3) showing that the Seebeck voltage difference $Us1\text{-}Us2$ between TEG1 and TEG2 is proportional to the temperature gradient $\Delta T = T1\text{-}T2$.

(3)

$$U_{S1} - U_{S2} = \alpha\left(1 - \frac{R_{TH\_HS}}{R_{TH\_HS} + R_{TH\_PEL}}\right)\cdot(T_1 - T_2)$$

where: R_{TH_HS} – thermal resistance of the heat sink [K/W]; R_{TH_PEL} – thermal resistance of the thermoelectric module [K/W].

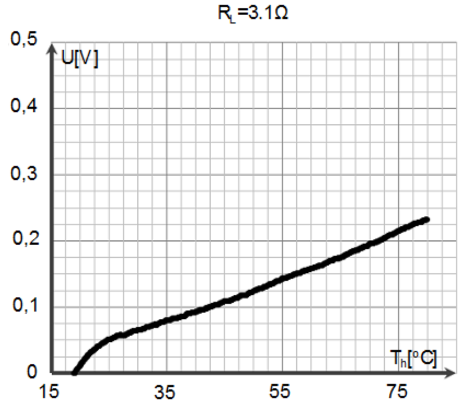

Fig. 5. Output voltage from the TEG versus temperature T_h of the liquid medium

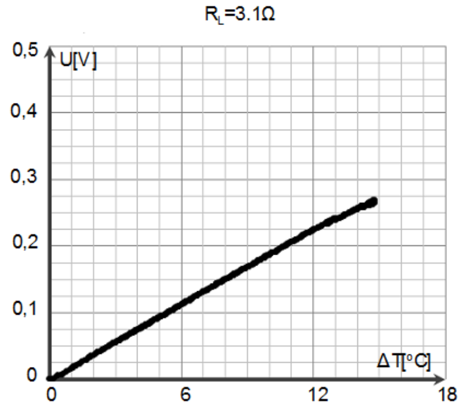

Fig. 6. Output voltage from the TEG against temperature gradient between two sides of the Peltier module

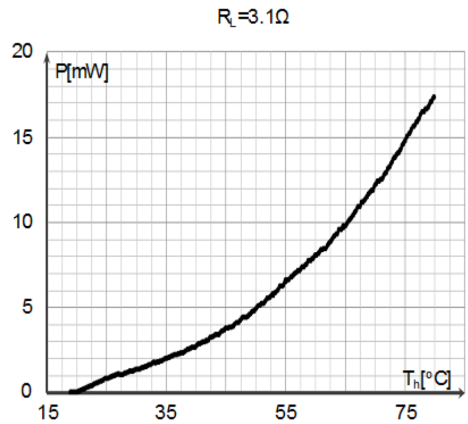

Fig. 7. Output power from the TEG against temperature T_h of the liquid medium

Thus, despite the fact that the Peltier modules at idle states do not indicate the appropriate temperatures that are necessary for determination of the heat energy consumption, it is the Seebeck voltage difference that appears to be the right indicator of temperature gradient between the inlet and the outlet. With this solution, the need for two dedicated sensors T1 and T2 in traditional metering systems can be completely eliminated.

Switching the Peltier modules into the idle state can be done regularly in very short periods of time, practically without disturbing the normal process of energy harvesting. Information about the voltage U_{S2} is transmitted by radio from TEG2 to TEG1. The electronic microsystem powered by TEG1 records pulses from the flow rate transducer PP, collects data from TEG2 about Seebeck voltage U_{S2}, calculate the heat consumption and transmit measured values to a central point.

With a very low efficiency of thermoelectric converter, only a small portion of the measured thermal energy is converted into electricity, so it itself distorts the measurement process to only a small extent.

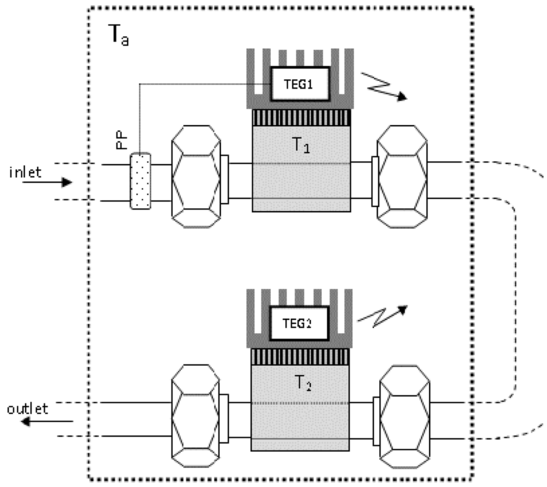

Fig. 8. A battery-less measuring setup for estimation of heat energy consumption

Conclusions

The new concept of heat metering relies in replacing two temperature sensors, measuring temperature difference *T1-T2* between the inlet and the outlet of the heating installation, by thermoelectric generators. Properly modeled combined thermoelectric modules as well as heat sinks provide Seebeck voltages that can be regarded as a good estimation of temperature difference.

With Seebeck voltage measurements made at the inlet and at the outlet of a system as well as with accurate flow rate measurement, the calculation of the supplied heat energy to an object can be carried out.

Thermogenerator that is both the temperature sensor and the source of electrical power, required for reading and transferring the measured data, is a very flexible tool that can simplify the process of installation and servicing of the metering systems, thereby increasing their reliability (no wiring whether for data transmission or electrical power supplying, no battery replacement).

The thermogenerator can provide adequate amount of energy to power the heat meter. With cyclic data transmission, the entire device is completely autonomous, characterized by practically infinite long life.

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