SIMULATION AND CALIBRATION TEST OF THERMOELECTRIC GENERATORS

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Abstract – Nowadays the consumer society uses giant amount of energy in its everyday life. A huge part of this energy is used for travelling and traffic. Field of the research project presented in this paper is the energy harvesting with special focus to the energy retrieving systems of electrical vehicles. Effects of thermoelectric generators (TEG) to the driving range of electrical vehicles is analysed, as well as simulation results and a new calibration system for TEGs are introduced in the paper.

Keywords: Thermoelectric generator, energy recovery system, Energy Harvesting, Comsol Multiphysics®

1. INTRODUCTION

Energy harvesting technology and its methods may have positive effect to minimization of energy consumption losses. Energy Harvesting is a general concept including wide range of methods and fields of application, in this project authors focused on diagnostic and development of special energy retrieving systems used for electrical vehicles. Methods summarised and presented in this paper have acceptable efficiency and reliability for using them in energy friendly electrical traffic systems. It includes study of thermoelectric generators' (TEG's) operation, simulations are performed by a final element program. The paper also includes detailed information on development of a new calibration and test system for TEGs, suitable for analysis of thermoelectric processes using different semiconductor elements and changing temperature difference between the cold and hot points from 10 to 400 °C.

2. METHODOLOGY

Energy harvesting methods and equipment provide energy recycling processes suitable for saving, storing and using energy losses at a later time for specially defined and limited applications. The main question in such system is what will be, what can be the energy retrieving and transferring medium? The theoretical answer is all energy sources suitable for using with some active sensing system can be suitable, which means that if we can define an active sensor for the actual energy source, providing electrical output signal without power supply, depending its power strength capacity it can be used for energy harvesting purposes. The main problem, that these output signals in most of cases have extremely low power limiting its use for energy harvesting. So we should select such systems where the operation of actuator-sensor system provides high enough energy losses for harvesting. The most obvious solution is to use mechanical energy sources, magnetic induction energy transformers using vibration, rotation, flow- or press change are well known. Probably the most widely used method for harvesting is conversion of the radiative energy. The light including infrared, ultraviolet and visible ranges, radiofrequency, airwaves, thermal radiation provide basic concepts for such systems using light elements, antennas, thermo- and piezo cells.

Table 1. Comparison of energy harvesting methods [1]
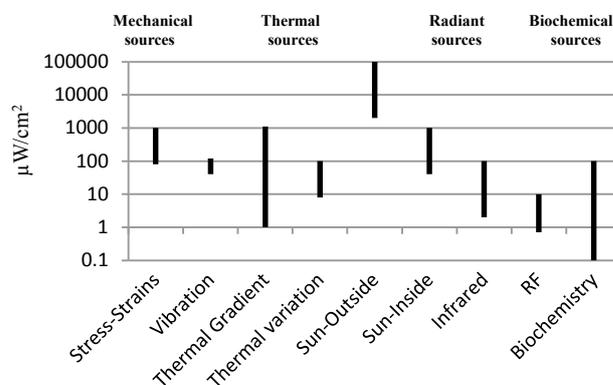
2.1 ENERGY HARVESTING IN ELECTRICAL VEHICLES

One of the most important limitation factors in global spreading of electrical vehicle is the problem of energy storage. In spite of continuously improving storage parameters of accumulators the average range of driving is about 100…150 km for a medium quality electrical car. In order to improve this performance energy retrieving systems using losses arising from movement dynamics are continuously under development. Calculating with normal driving practice and traffic conditions the most efficient methods to use for harvesting are actuating vibration generated by road scragginess, thermal dissipation of electrical parts, as well as using breaking energy generated by

traffic dynamics. Such system is the KERS (Kinetic Energy Recovery Systems) introduced in 2009 in Formula 1 race. The KERS system is able to convert kinetic energy arisen during breaking of the car to electrical energy and to store it for the speed-up using electrical drive. It means that in speed-up operation phase besides of combustion engine also an electrical motor is included into the driving system of the car.
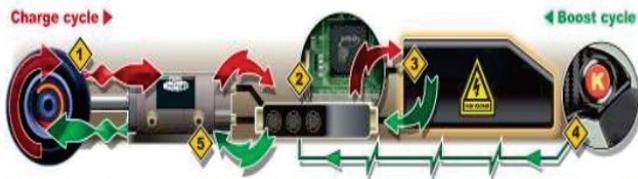
WORKING PRINCIPLE

Fig. 1. Kinetic Energy Recovery System of a Formula 1 car [2]

Also a well known, new but more and more widely used energy retrieving method is the shock-absorber power generators. Road irregularities, swales and potholes cause discomfort for car drivers and passengers, damage in cars, but their dynamic effects may be used in absorbers for energy harvesting. Traditional shock absorbers dissipated this energy in form of heat, but the energy can be used by different was, like mechanical or electromagnetic power generators. MIT has developed a hydraulic system for power generation [3], but it seems the most effective method in these days based on magnetic field theory and uses electromagnetic systems, which are not effecting to the stability of the car while generating power.
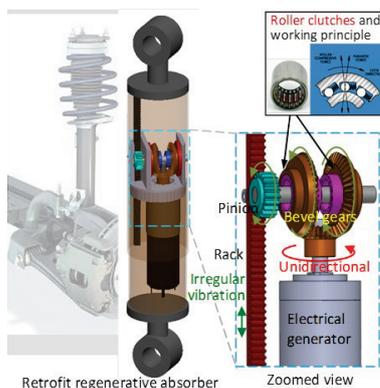

Fig. 2. Shock-absorber power generator system [4]

The third and probably the most promising pillar of the energy harvesting in electrical vehicles is the heat.

Electronic devices of the driving system require intensive cooling, and also energy losses of the electrical motor are dissipated in form of heat, so also cooling system is necessary for optimal operation. Vehicles usually use water cooling with air ventilation and additional energy is used for keeping the vehicle's motors and driving elements on optimal operational conditions.

Thermoelectric generators transform heat energy into electrical energy according to temperature difference between the cool and hot point of the generator. Hot point is heated by electrical motor and power electronic elements while cool point is placed to wind at ambient temperature. In ideal situation, while motor operation efficiency is still good driving elements are heated approximately up to 80°C. The ambient wind can keep the cold point in average at 20°C. Depending on TEG parameters harvested energy can be calculated. The following section of the paper discusses TEG operation and simulation of idle voltage in function of temperature difference.

2.2. SIMULATION OF THERMOELECTRIC GENERATOR PERFORMANCE

Practically electrical losses are dissipated only in form of heat, electrical and electronic producers spend huge resources to develop ideal cooling systems for electrical equipment. As thermoelectric generators use temperature difference for operation besides of energy harvesting it has an additional advantage which is the cooing effect. Our research group has developed a system suitable for diagnostic and evaluation of different TEGs. The system is presented in details in section 2.3.

TEGs have three main parts: N-type semiconductor, P-type semiconductor, and also a copper conductor providing contact surface between semiconductors. The most commonly used semiconductor is Bismuth Telluride (Bi_2Te_3). The element is installed between two insulating surfaces made of ceramic material (Al_2O_3) in most of cases. [5]
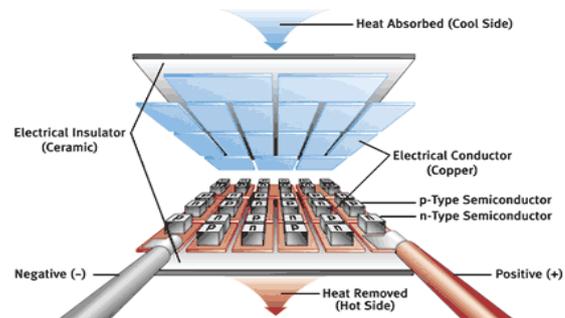

Fig. 3. Theoretical structure of thermoelectric generator [6]

Theory of operation of TEGs is based on thermoelectric phenomena and processes which can be described by Seebeck, Peltier and Thomson effects.

The Seebeck effect means that temperature difference between the hot point (junction point of two wires of different materials) and cold point (other, not connected ends of two the wires) generates electromotive force between the wires ends at cold point. The Peltier effect is the opposite of the Seebeck effect, when the same two wires connected in one end are excited by current, the hot junction point is warming or cooling depending on the current flow direction. The Thomson effect describes heat generation or abstraction in a conductor depending on material of the conductor, on current flow direction and level in the conductor.

In order to analyse TEGs operational mechanism thermoelectric field equations have to be defined and solved. Processes were simulated using COMSOL Multiphysics® final element modelling and simulating software.

COMSOL Multiphysics FEM program can be used for simulation different physical applications. It includes user

friendly interfaces, efficient solving algorithms and provides possibility for full control of network generation. Connected physical processes described by partial differential equations can be modelled and calculated. It is useful for engineering modelling, determination of geometries, generation of networks, determination of physical conditionals, for problem solving and result presentation. [7]

Determination of adequate thermoelectric equations was the first step for simulation. Electrical current balance and Heat energy balance can be defined as

$$-\nabla \cdot (\sigma \nabla V) = 0 \qquad (1)$$

$$\begin{cases} \rho C_p \dfrac{\partial T}{\partial t} + \nabla \cdot q = Q \\ q = -k\nabla T + \underline{\underline{PJ}} \end{cases} \qquad (2)$$

where
σ: electric conductivity [S/m]
V: electric potential [V]
ρ: density [kg/m^2]
C_p: heat capacity [J/(kg·K)]
T: temperature [K]
q: heat flux [W/m^2]
k: thermal conductivity [W/(m·k)]
P: Peltier coefficient [V]
J: current density [A/m^2]
$Q = j \cdot (-\nabla V)$: Joule heating [W/m^2]

Thomson's second relation between Seebeck (S) and Peltier (P) coefficients is defined as follows

$$P = -ST \qquad (3)$$

Conversion of equations can be converted using theory in Energy balance can be transferred to a weak form multiplying each side of energy balance by a test function T_{test} and integrating over the computational domain Ω:

$$0 = \int_{\Omega} \left[-\rho C_p \dfrac{\partial T}{\partial t} T_{test} + (-k\nabla T) \cdot \nabla T_{test} + (PJ) \cdot \nabla T_{test} + Q T_{test} d\Omega \right] -$$

$$- \int_{\partial\Omega} (q \cdot n) T_{test} \partial\Omega \qquad (4)$$

For validation of simulation the TEC1-24118T125 TEG was selected consisting of 241 Bismuth Telluride semiconductors and aluminium –oxide insulators. After determination of exact sizes of elements the geometry was developed in the simulation program. In the following step parameters of materials of each element were defined.

Simulations were performed for two different semiconductors. Semiconductors were selected according to efficiency requirements. As TEGs made of Bismuth Telluride and Lead Telluride semiconductors have highest efficiency in the usual range of electronic devices heat.

Table 2. Material parameters of simulation elements

	Bismuth Telluride	Lead Telluride	Copper	Aluminum Oxide
Seebeck coefficient [V/K]	p: 200*10^{-6} n:-200*10^{-6}	p: 187*10^{-6} n:-187*10^{-6}	3,8*10^{-6}	-
Electrical conductivity [S/m]	1,1*10^5	6,0976*10^4	6*10^7	1,502*10^{-7}
Thermal conductivity [W/mK]	1,7	1,46	400	35
Heat capacity [J/kgK]	554	151	385	730
Density [kg/m^3]	7700	8160	8800	3965

Simulation were performed for several temperature ranges. The range means the temperature difference between the cold and hot points of the TEG. The starting range was 60°C as it is the most probable range for electrical vehicle operation, when calculating with 20°C ambient temperature and 80°C operational temperature of the electrical motor. The other range was defined with 25°C cold point, as the calibration system uses water from household water supply and the water in June when measurements were performed the water temperature in tube system was 25°C in the site of tests. The hot point was set from 50 to 250°C in 7 steps. The maximal temperature difference is 300°C by specification of the TEG. The temperature was defined in the simulation to the outside surface of ceramic insulation. The aim of the simulation was determination of electrical energy generated by TEG in different operational conditions and at different temperature ranges. The first contacting surface of the element was defined to constant 0 V potential and the potential of the other contact surface was examined. The simulation calculated (4) equation in each points defined by Mesh. [8] [9] [10]

2.3 CALIBRATION SYSTEM FOR THERMOELECTRIC GENERATORS

Validation of TEG modules of different types and sizes require a calibration system of high reliability and repeatability therefore the research group decided to develop a calibration system for our special needs.

Temperature of the heated side is generated by a 450 W Infrared Top Ceramic Heater. It can generate 750 °C temperature, therefore housing with special heat insulation should be used. The house is made of Bakelite plate width of which is 15mm. The Bakelite is one of the best heat insulating material with 0.23 [W/mK] heat conductivity coefficient. Inside of the Bakelite housing a secondary insulation is applied which made of a special non-combustible asbestos alloy. This material is used for inner insulation of combustion chamber in household furnaces. Between the heater piece and TEg an aluminium inner spreader is included in order to provide equal temperature on the surface of the TEG. As there are many different TEG sizes are available from different prodcers, modular aluminium spacers are designed for TEGs. These spacers are used for flexible assembling and insertion

of K type thermocouples measuring temperature of hot point. The spacer also ensures the homogeneous temperature on the full surface of TEG's.

For cooling of the cold point a flow water cooler is used which is connected to household water tube. Also an aluminium spacer measuring temperature of cold point is inserted between the cooler and TEG module. Aluminium spacers are designed for all standard sized TEGs in order to ensure homogeneous temperature distribution on the full surface.
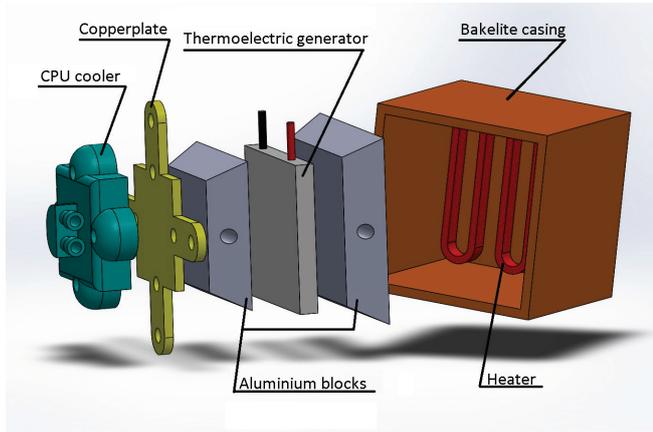

Fig. 4. Construction diagram of the measurement system

Control of tests are developed using National Instruments hardware and software.
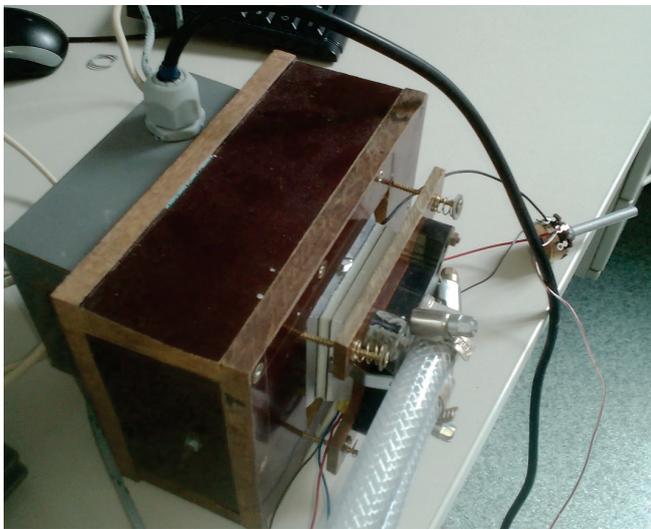

Fig.5. Measuring and calibrating equipment

2.4. MEASUREMENT AND CONTROL SYSTEM

Measuring and control system is developed using National Instruments hardware. It includes one analogue voltage input module, one analogue current input module, one analogue output module and one thermocouple module. Analogue input modules are used to measure voltage and current of TEGs output. These modules have 24 bits resolution, ± 10 V and 5 A full scale values, so the range and accuracy fulfil requirements of tests.

The analogue output module is used to control heating insert. The calibrating equipment includes a triac-opto-triac control ensuring control signal for module.

The thermocouple module is used for measuring the hot and cold points. It is equipped with cold-point-compensation and the resolution is also 24 bits.

2.5. MEASURING AND CONTROL SOFTWARE

The measuring and control software is developed in LabView of National Instruments. It is a graphical programming environment, providing effective and fast development phase.

The temperature is calculated as average of 10 measured points in each seconds. The main task of the calibrating equipment is to keep the temperature difference between the cold and hot points stable on a defined level. The measured and averaged temperature data is sent to a PID control, parameters of which are defined by Ziegler-Nichols method.

Output of the PID controls duty circle of a square wave used in a virtual PWM generator. The signal then is sent to the analogue output and a triac-opto-triac control with 50 Hz refresh frequency.

Sampling frequency of 1 kHz is used to measure TEG module's voltage and load resistance's current. The aim of calibration is to define maximum level of harvested power of TEGs on a defined temperature difference level. The power will be the highest when the inner resistance of the module is equal to the lad resistance. The load resistance is calculated by software from the measured voltage and current.
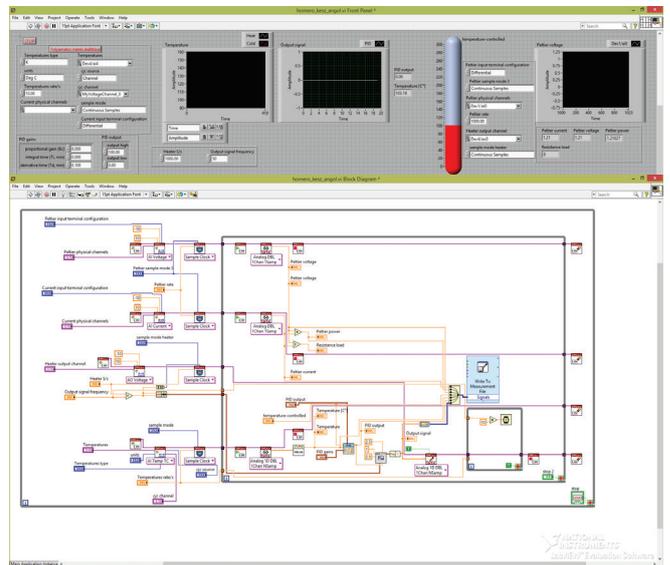

Fig. 6. Measuring and control software

3. RESULTS

One of the most important parameters of TEG is the open circuit voltage, because the characteristic of TEG shows that maximum power generation level can be reached when the load resistance is equal to internal resistance of TEG, so the TEG internal resistance and the generated voltage theoretically defines the power generation level. In simulation of TEGs we have set different temperatures on the cold and hot points of the module. Geometry used in the COMSOL

Multiphysics® FEM program is similar to the geometry of TEG type of Custom Thermoelectric Inc. 2411G-7L31-15CX1 [11]. As the producer of TEG's until now has not provided information of the exact material of TEGs, we have used in simulations ideal Bi_2Te_3 and PbTe materials. Simulated temperature differences and open circuit voltage are shown on Fig. 7-8. for specified geometry.
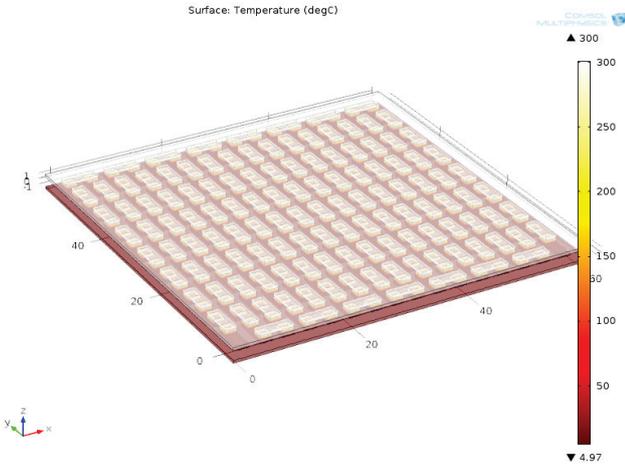

Surface: Temperature (degC)

Fig. 7. Simulation of temperature difference of TEG

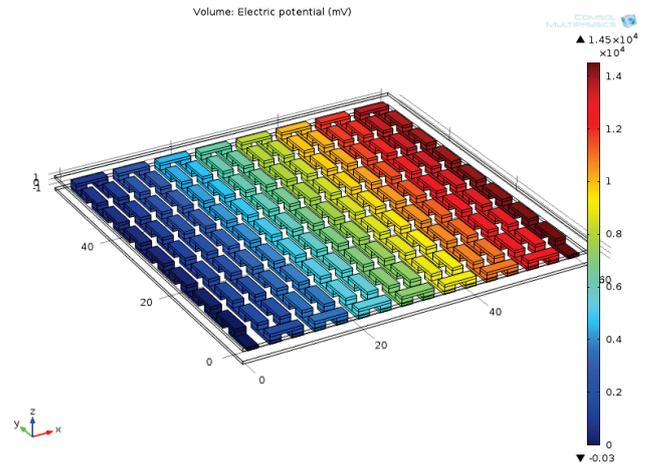Volume: Electric potential (mV)

Fig. 8. Simulation of open circuit voltage

Open circuit voltage in function of temperature difference is show non Fig. 9. for two different semiconductor applications. Colours of the figure are as follows: simulated Bi_2Te_3 – green, simulated PbTe – purple, Custom Thermoelectric Inc. 2411G-7L31-15CX1 open circuit voltages by specification – red [11], measured open circuit voltages – blue. All data are presented in function of temperature difference.
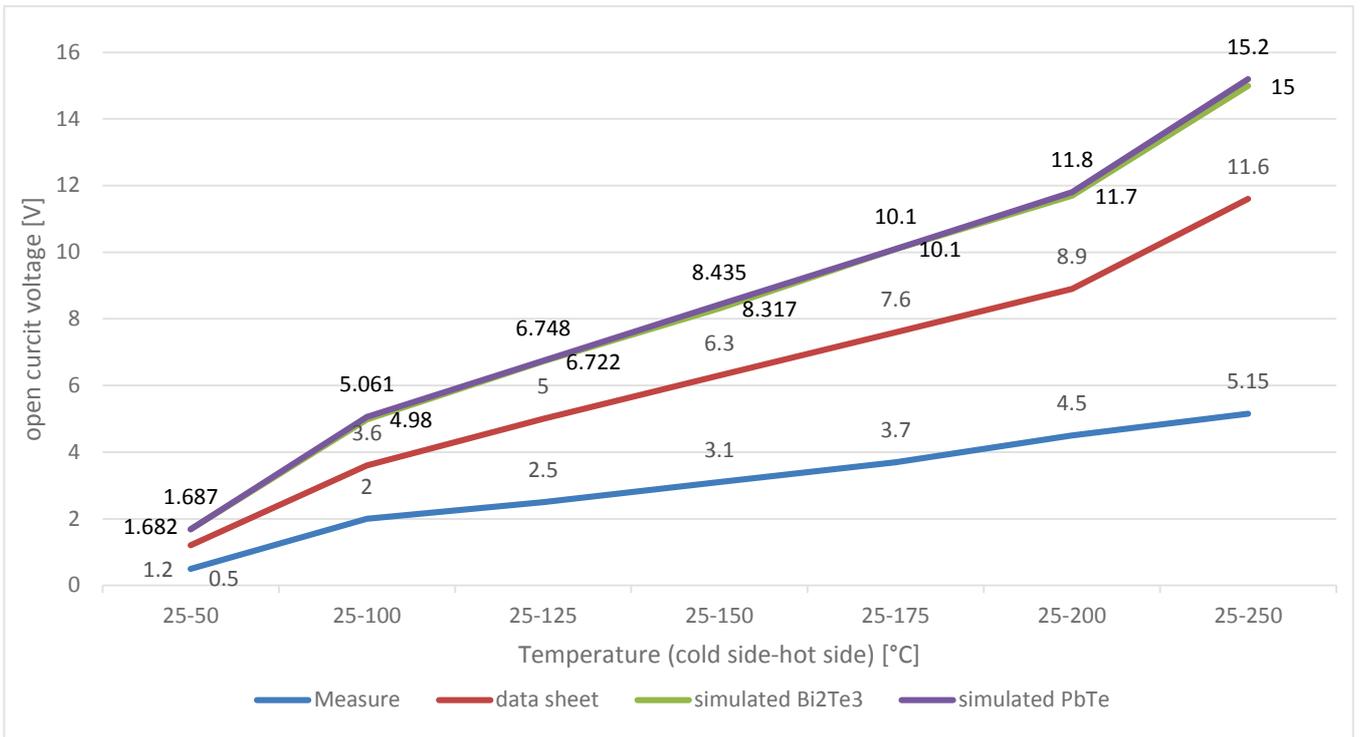

Fig. 9. Simulated open circuit voltages of TEG in function of temperature difference

The graphs show relatively high differences, which come from the material definition, as in the simulation ideal semiconductor materials are used causing extremely high values. The measured values are lower than expected by simulations and specifications. One of the main reason of this is measuring the temperature not directly on the surface of the TEG, but in the middle of the aluminium insert. Also the instability of the temperature of the cold point by 2-3 °C caused measuring errors.

In the project application the most probable range of the hot point is between 25 and 100 °C. In this range approximately 3 V_{dc} can be generated providing 3-5 W power. This values seems quite low but serial and parallel connections of many such modules on the heated surfaces may provide multiplying efficiency of energy harvesting in a vehicle.

Optimization of TEG's working range and point are going on, validation results will be presented in the oral presentation at the XXI World Congress IMEKO.

4. CONCLUSION

The simulation and practical validation measurements have proved that TEGs can be used in energy harvesting applications, but they can provide specification values only in ideal environment.

Development and application of simulation and calibration system of TEG's provides additional information for research of energy harvesting efficiency. Developing new methods or improving existing systems requires multi- and interdisciplinary research activity, including material science, physics, electronics, information technology, etc., and results may lead to increase of driving range of electrical vehicles.

80°C is the minimal operational temperature in an electrical vehicle, which is generated in normal operational conditions without any additional effects or energy infusion. In the recent vehicles additional energy is used for cooling electronics and the motor. TEG applications are able to use heat losses for energy generation causing in the same process heat abstraction from warming parts, so secondary energy saving is derived from using less energy for cooling. Researches in the field are at the begin and going on, but results so far already underline future importance of TEGs in electrical vehicles.

ACKNOWLEDGMENTS

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