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Feasibility study of a new thermoelectric conversion device utilizing the temperature differences in forest soil[1]

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Abstract. The new thermoelectric device can be powered for forest wireless sensors stably. There is a temperature difference between the forest's various soil layers—it is be possible to make use of this temperature difference to generate electricity. This device is mainly composed of heat pipes and thermoelectric power generators (TEGs), which can transfer soil heat to electricity. By simulating the forest soil environment, the experimental results show that for a stable soil temperature, the device can generate approximately 298.5 mV, which is superior to other existing device. The device provided a new type of power supply for wireless sensors. The results provide the theoretical and technical basis for a form of power generation that utilizes a forest's soil temperature.

Key words. Wireless sensor, soil heat resource, thermoelectric power generation.

1. Introduction

Because of geological movement, climate drought, man-made reasons, forest fires and mudflows occur frequently. Early and timely prevention and monitoring of forest fires [1] is essential for reducing the loss of natural resources and mitigating economic losses [2, 3]. It is also important to monitor the forest structure and the mortality of tree populations [4]. Forest wireless sensors utilize meteorological and remote sensing methods (integrated with data mining methods) to monitor the impact of drought on forests [5]. Wireless sensors can be used to uncover a forest's structure and explore the risk of the forest changing and evolving ecologically, monitoring wildlife in its

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forest habitat [6], forest residue burning [3], vegetation changes, and precipitation of forest biota [7]. This requires the support of real-time systems related to forest monitoring. Having forest fire detection systems with real-time processing can lead to excessive energy consumption though. The application of wireless sensor network monitoring technology is an aspect of precision monitoring technology [8]. It is integral to the entire forest monitoring system, which has become a key concern in many countries in recent years [9, 10]. Nowadays sustainable natural energy can take the form of solar energy, wind energy, hydro energy, vibrational energy, and geothermal energy; these are examples of sustainable acquisition and conversion of natural pollution-free energy. In forest environment there is little advantage to using solar energy because electricity cannot be generated at night. When it is rainy, while the wind in the forest is unreliable, too. Therefore, relying on solar or wind energy in forest is not feasible. To understand how we might be able to generate power in forests, it should be noted that in general many countries have decided to utilize generators that generate electric power from waste heat via industrial waste heat, garbage incinerators, or waste heat from automobiles.

In recent years, a variety of devices have been developed to recover waste heat: for example, an apparatus was developed to recover thermal waste [11]. Vehicle exhaust can be recovered by heat pipes and thermal batteries [12]. Meanwhile, Andre Moser developed a thermoelectric collector to utilize the natural temperature difference between a building's walls and the surrounding air to essentially turn this energy into electrical energy that is stored in a capacitor. However, no device has been developed to collect energy from the temperature differences in the soil [13]. Additionally, Meydbray built a harvester that could utilize the temperature differences through different degrees of sun irradiation in forests; however, the system did not function very efficiently. In China, most research into thermoelectric power generation aims to produce either power generators or materials that can be used for thermoelectric power generation. Additionally, a thermoelectric generator device has been proposed for automotive exhaust gas conversion [14] and industrial waste heat conversion [15]. At present, solar energy and waste heat generators are used to study the heat transfer efficiency of such system [16]. Deng built a thermoelectric conversion system model and applied it to cars, which verified the energy-saving effects of using thermoelectric collectors in cars [17]. Meanwhile, Zhe invented a thermoelectric conversion device that utilizes solar energy as the main energy source; however, those devices cannot be applied in forest environments [18]. The leaves of trees in the forest are thick so that it is difficult to utilize the solar energy.

Because of the low thermal conductivity of soil and atmospheric effects, there is a temperature difference among forest's soil depth, i.e., there is a temperature difference between the upper and lower layers of soil. Based on the Seebeck effect, any temperature difference can be used to generate electricity [15, 19]. If the temperature difference between the forest and the soil surface were utilized for power generation, it could provide a stable and reliable micro power source for wireless sensors in a forest. The key technical issue is how to transmit the energy generated from the soil's heat to the TEG. Having been invented only in recent years, heat pipes are a new technology that has a superior metallic heat transfer performance compared with traditional systems; it also provides a way to efficiently transfer heat energy. One successful study has demonstrated the transfer of heat from lower layer of soil to upper layer of soil through heat pipe. The main feature of heat pipe is its small thermal resistance, fast heat transfer characteristics, high efficiency, lightweight, small in size, and reliable. For general applications of heat pipe technology, however, its thermoelectric conversion efficiency needs to be improved.

Studies have shown that heat pipes can be buried in the ground to facilitate heat exchange with the ground. A large number of studies have focused on the use of heat pipes that transfer heat from underground to the surface. A snowmelt system for roads was designed to melt snow and ice using geothermal energy. Thus, previous research can lay the theoretical and technical foundation for a forest soil thermoelectric power generation system as well as laying the foundation for exploring a heat transfer mechanism from the ground to a thermoelectric generator through the heat pipe. Thermoelectric generator connected to a heat pipe can be applied in the forest environment to solve the issue of power supply problem for forest wireless sensor network.

Thermoelectric conversion technology is applied in many areas; however, thermoelectric power supplies for forest wireless sensor applications are still lacking. The thermoelectric conversion device presented here has an increased heat transfer efficiency compared with that demonstrated in the original study. The design of our thermoelectric conversion device depends entirely on heat at the soil's surface, which is more suitable for a forest environment. The particular structure of the device is superior to that of others, which were not specifically designed for forestry applications. The main purpose of our study was: a) the design and fabrication of a thermoelectric conversion system and the improvement of the model for simulating the soil environment and b) to test the performance of the thermoelectric conversion system. We aimed to verifying the feasibility of thermoelectric power generation from soil, to improve the thermoelectric conversion efficiency, and to conduct the research in forest-like conditions.

2. Materials and methods

Thermoelectric generators are able to directly convert thermal heat differences into electricity when there is a temperature difference between the two ends of a thermoelectric material. The thermoelectric effect is actually based on either the Seebeck effect, the Peltier effect, the Thomson effect, the Joule effect, or the Fourier effect. Modern thermoelectric power generation devices are based on both the Seebeck effect and the Peltier effect. Thermoelectric power generation has the advantage of being environmentally safe, with neither noise nor pollution generated. To generate electricity, many p-type and p-type semiconductor legs are sandwiched between two electrically insulating materials that have thermoelectric properties. There is a linear relationship between the thermal electromotive force and the temperature difference between the hot and cold faces. The thermoelectric conversion figure of merit Z is related to the properties of the semiconductor material. The figure of merit is based on the material's thermoelectric transfer properties:

$$Z = \frac{(N\alpha)^2}{KR}\,, \tag{1}$$

where R is the internal electric resistance, K is thermal conductivity and N is the number of thermoelectric couples incorporating p-type and n-type semiconductor elements. According to the above definition, the figure of merit Z is related to the Seebeck coefficient α, the geometric dimension of the semiconductor galvanic couple, the total resistance of the thermocouple arm, and the thermal conductivity.

The proposed thermoelectric conversion device includes a heat pipe, eight TEGs, two copper sleeves, and copper fins; its structure is depicted in detail in Fig. 1.

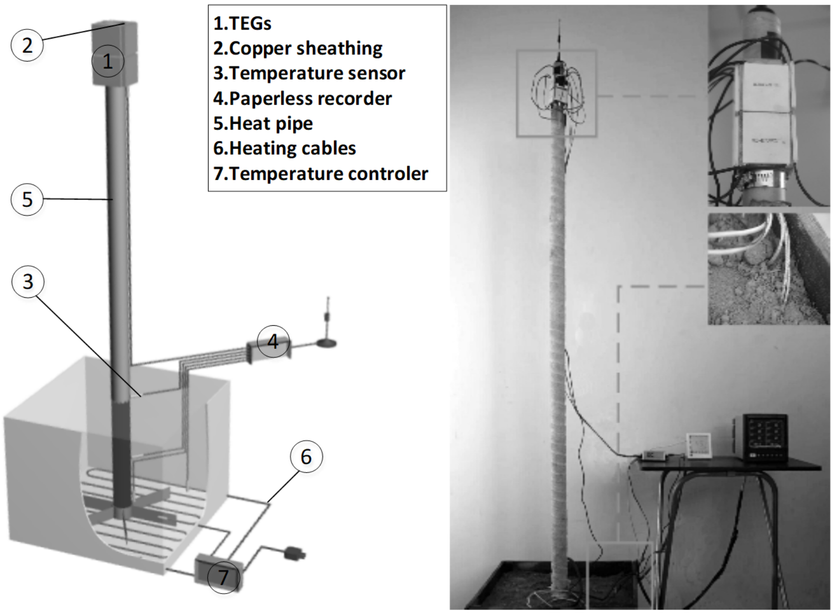

Fig. 1. Thermoelectric conversion device

Three types of heat are relevant to thermoelectric conversion devices: the heat generated by the heat conduction between the soil and the heat pipe, W_{sh}; the heat generated by the heat conduction between the soil and the copper sleeves, W_{hc}; and the heat generated by the heat conduction between the thermoelectric generator and the copper sleeves, W_{ct}. The expression for W_{sh} is as follows:

$$W_{\mathrm{sh}} = -hA\frac{\partial T}{\partial n}\,, \tag{2}$$

where h, n are the thermal conductivity coefficient and the unit outward normal, respectively. Symbol A is the contact area between the heat pipe and soil and T is the temperature of heat pipe in the soil.

Thermal energy absorbed by the heat pipe through the soil is transported from an evaporator to a condensation section. Then, the heat energy is transmitted to the copper sleeves by heat conduction:

$$W_{\mathrm{hc}} = W_{\mathrm{sh}} - \Phi_{\mathrm{b}} - q_{\mathrm{C}} - q_{\mathrm{l}}\,. \tag{3}$$

Here, Φ_{b} is the loss heat of the heat pipe, q_{C} is the loss heat of the copper bush and q_{l} is the loss heat of other parts.

Soil thermal energy absorbed by the heat pipe is scattered in five directions. Eventually, the energy absorbed by the thermoelectric energy collection module is calculated according to formulae

$$W_{\mathrm{ct}} = W_{\mathrm{hc}} - \Phi_{\mathrm{Cu}} - q_{\mathrm{Cua}} - q_{\mathrm{l}}\,, \tag{4}$$

where

$$\Phi_{\mathrm{Cu}} = \varepsilon_{\mathrm{c}} A_{\mathrm{e}} \sigma_{\mathrm{b}} \left(T_{\mathrm{c}}^4 - T_{\mathrm{c}}^4\right)\,, \quad q_{\mathrm{Cua}} = \lambda_{\mathrm{c}} A_{\mathrm{c}} \Delta T_2\,, \tag{5}$$

where ε_{c}, σ_{b}, A_{e}, A_{c}, T_{c}, T_{a} are the emissivity of thermoelectric energy collection module average surface of energy conversion system, Stefan Boltzmann constant, thermoelectric energy conversion coefficient of the surface area of radiation, convection area between the system surface layer and air in the process of energy collection, the copper bush average surface temperature and average temperature of the environment of thermoelectric energy conversion system, respectively.

The power obtained from the thermoelectric electric generator is given by:

$$q_{\mathrm{TEG}} = Q_{\mathrm{h}} - Q_{\mathrm{l}}\,, \tag{6}$$

where q_{TEG}, Q_{h}, Q_{l} are power emitted from thermoelectric power generation cell current, heat flows of the hot side, the heat flows of the cold side, the heat generated by the Peltier effect, the heat passing through the semiconductor compose Q_{h} and Q_{l} together. The heat generated by the Peltier effect, the Joule heat in the semiconductor, and the temperature difference based on the above analysis may be given as

$$Q_{\mathrm{h}} = \alpha_{\mathrm{ab}} I T_{\mathrm{h}} + \lambda (T_{\mathrm{h}} + T_{\mathrm{l}}) - \frac{1}{2} R I^2\,,$$

$$Q_{\mathrm{l}} = \alpha_{\mathrm{ab}} I T_{\mathrm{l}} + \lambda (T_{\mathrm{h}} - T_{\mathrm{l}}) + \frac{1}{2} R I^2\,, \tag{7}$$

where α_{ab}, T_{h}, T_{l}, λ, I, R are the total Seebeck coefficient of thermoelectric power generation sheet, temperature of the cold side of the thermoelectric generator, temperature of the hot side of the thermoelectric generator, total semiconductor chip thermal conductivity of the thermoelectric power generation, current in the closed circuit and sheet resistance of the thermoelectric power generation, respectively.

The heat flow through the TEG is a function of the performance of the thermoelectric materials and thermoelectric component geometries. It can also be described as follows:

$$q_{\mathrm{TEG}} = N(\alpha_{\mathrm{p}} - \alpha_{\mathrm{n}}) I T_{\mathrm{u}} + K (T_{\mathrm{u}} - T_{\mathrm{d}}) - \frac{1}{2} R I^2\,. \tag{8}$$

In (8), α_{p} is the P-thermoelectric power generation of TEG, α_{n} is the N-thermoelectric power generation of TEG, T_{u} is the high temperature of TEG, T_{d} is the low temperature of TEG, and K is the total thermal conductivity of TEG. Finally, N denotes the number of P-N pairs in TEG.

From the above relationship, we can find that

$$W_{\mathrm{ct}} = q_{\mathrm{TEG}}\,. \tag{9}$$

Therefore, the proposed thermoelectric conversion device is theoretically feasible. The proposed thermoelectric conversion device includes a heat pipe, eight TEGs, two copper sleeves, and copper fins. As shown in Fig. 1, the heat pipe's evaporator is located in a steady external soil heat source (simulating a forest's soil environment) in which the temperature is higher than the air temperature, which was controlled by air conditioning. The principle of how a heat pipe works is also shown; the heat pipe's working fluid evaporates and becomes a gas as the soil heat is absorbed at the evaporator side. Under atmospheric pressure the working gas condenses into droplets when it arrives at the condenser and transfers the heat to the copper sleeves. Then, the working liquid travels back to the evaporator end, achieving an energy self-transfer after repeated cycles. A heat pipe's internal processes include two-phase flow and phase change heat, and so the inner heat transfer principle is very complex. The simplified model of heat pipes divides the heat transfer process into three parts: the heat exchange in the condensation section, the heat exchange at the evaporator, and the heat exchange with the insulation of the heat pipe. The adiabatic section of the heat pipe was covered with asbestos to reduce the loss of heat. There were also two copper sleeves set into the condensation section of the heat pipe. On each surface of the copper sleeves four TEGs were inlaid. These kind of heat pipes do not have wicks and they depend on the gravity principle. Therefore, the inner pressure of the heat pipes is determined by the vapor pressure of the evaporating working liquid. The working liquid will evaporate when the surface of the heat pipe is warm. The heat pipe produces a pressure difference because the vapor temperature and pressure of the heat pipe's evaporator is slightly higher than its other parts, which promotes steam flow to the condensation section of the heat pipe. When the steam condenses on the heat pipe's wall, it releases heat, which is transferred to the condensation section. Then, the condensed liquid returns to the evaporator under gravity. This process will loop as long as the heat source continues to exist.

To build an experimental power system platform with a steady external heat source (simulation of the soil environment) we used a heat pipe, eight TEGs, two copper sleeves, and copper fins. There were four temperature sensors on the heat pipe. The first temperature sensor was placed on the evaporation section. The second was placed on the adiabatic section, while the third was placed on the evaporation section. The last one was used to record the surrounding air temperature. The temperature sensors were used to monitor and record the temperature of the various parts of the heat pipe. There were two parallel copper sleeves mounted on the evaporator section of the heat pipe; one TEG was placed on each side of it. Therefore, there were eight TEGs on the copper sleeves in total, which were used to connect the TEGs and the heat pipe. The soil's heat can be transferred through the heat pipe and the copper sleeves to the TEGs. Then, the heat can be converted to electricity through the TEGs based on the Seebeck effect. Our measurement results verify the mathematical model. We proposed an optimum design for the thermoelectric conversion device, which provides the technical basis for improvements to electricity generation systems.

3. Results

As shown in Fig. 1, there are three temperature measurement points distributed on the heat pipe that gauge the evaporator temperature B, the section temperature C, and the adiabatic section temperature D. The air temperature has the label A. The length of the heat pipe is 2 m, its diameter is 38 mm, and its wall thickness is 3 mm. The working liquid volume takes up 1/40th of its entire volume. The condensation section of the heat pipe in this experiment was covered with asbestos. There were two sets of control experiments. The thermoelectric conversion device was placed in both soil and water. The air temperature was 14 °C, which was controlled by air conditioning. The temperature of the soil was changed by heating cables buried in the soil. The temperature difference between the soil and the air ranged from 5 to 20 °C. The temperature change of each of the three parts of the heat pipe was recorded for every 1 °C of change. Although the heat transfer coefficient of the heat pipe is high, the customized heat pipe in this device is larger in diameter than that of a conventional heat pipe and is also longer. In addition, the heat transfer coefficient of water is much higher than that of soil. The results of the measurement are illustrated in Fig. 2. First, the heat transfer occurs much faster for a heat pipe with asbestos than for one without it. The maximum temperature of the evaporation section of the heat pipe without asbestos remains constant, which takes almost 30 min. According to Fig. 2, it takes only 15 min for the pipe to reach its maximum temperature after which its temperature remains constant. Simultaneously, using asbestos significantly reduces heat loss to the surroundings; the temperature of the evaporator is also higher than before. The temperature of the evaporation section of the heat pipe with asbestos was by 2 °C higher than that without asbestos. Second, compared with water, the heat transfer coefficient of soil is much lower. In Fig. 2, it can be seen that it took nearly 70 min for the heat pipe to reach a constant temperature. Based on the data in Fig. 2, we exploited the temperature difference, which was less than 2 °C, between the three parts of the pipe. In particular, the temperature difference between the evaporator and the adiabatic section was only 1 °C. The temperature of the heat pipe was constant after being in the soil for about 70 min. This shows that the heat pipe has good isothermal properties and a low thermal resistance. Nevertheless, the temperature of the top of the heat pipe was a bit lower, because there is a cap on the inner heat pipe to seal the working liquid. Hence, there is only a 1 °C difference between the end of the heat pipe and 1.5 m up the heat pipe. When the heat pipe works stably, the temperature difference between the heat pipe and the heat resource is 6 °C. According to the definition of the Carnot efficiency, the heat transfer efficiency cannot be one hundred percent. Therefore, there is a heat loss of 6 °. After a series of experiments this value remained constant. The physical parameters of TEGs are given in Table 1.

As can be seen in Figs. 3 and 4, there were some irregular data. First, for a low temperature difference of 5—9 °C, the amount of electricity generated by the device was very small. As the temperature difference increased, the voltage and current noticeably increased. When the resistance in the parallel circuit was as large as the TEG's inner resistance, the voltage was larger than for other resistance values for the same temperature difference.

Table 1. Physical characteristics of TEG

MPN	Couple	V_{DC} (V)	R_{TE} (Ω)	I_{MAX} (A)	P_{MAX} (W)	T_{MAX} (°C)
TEG-12708T237	127	3.4	5	1.81	6.2	250

Second, there are further abnormal data in the chart for temperature differences between 18 and 20 °C. Through repeated measurements and analyses the reason behind the abnormal data was found. One side of the TEG was adhered to the hot section, while the other part was exposed to the relatively cold air. According to the first law of thermodynamics, heat always spontaneous transfers from high to low temperature objects without external force being necessary. Hence, both sides of the TEG are dynamically consistent. We conducted another experiment to compare the difference in electricity that is generated when the temperature rises and falls by 1 °C for each temperature up to 20 °C (with 1 °C intervals). When the air temperature was 14 °C, the temperature difference between the air and the soil was adjusted from 5 °C all the way to 20 °C; the recorded data is presented in Fig. 3. This verifies that no matter what the temperature of the cold side of the TEG is to begin with, once the temperature difference between the cold side and hot side (air and soil temperature difference) reaches a constant value, the value of the generated electricity will also be stable.

As shown in Fig. 5, we varied the number of thermoelectric generators in the device while keeping the other conditions constant. As the temperature difference increased, the voltage in the three different circuits increased correspondingly. There was an approximately linear relationship between the behaviors of the three circuits. The voltage in the circuit with eight TEGs was nearly four times that of the voltage in the circuit with four TEGs and eight times that of the voltage in the circuit with one TEG. The voltage initially increased very slowly for low temperature differences. As the temperature difference increased, the voltage increased more. The tests showed that the more TEGs there are, the greater the voltage is that is generated for the same temperature difference. The voltage was largest for the largest temperature difference.

4. Conclusion

This paper investigated a thermoelectric conversion device that can be used as a power supply for forest wireless sensors. The thermoelectric conversion device is based on the Seebeck effect and heat pipe working principle. The main conclusions

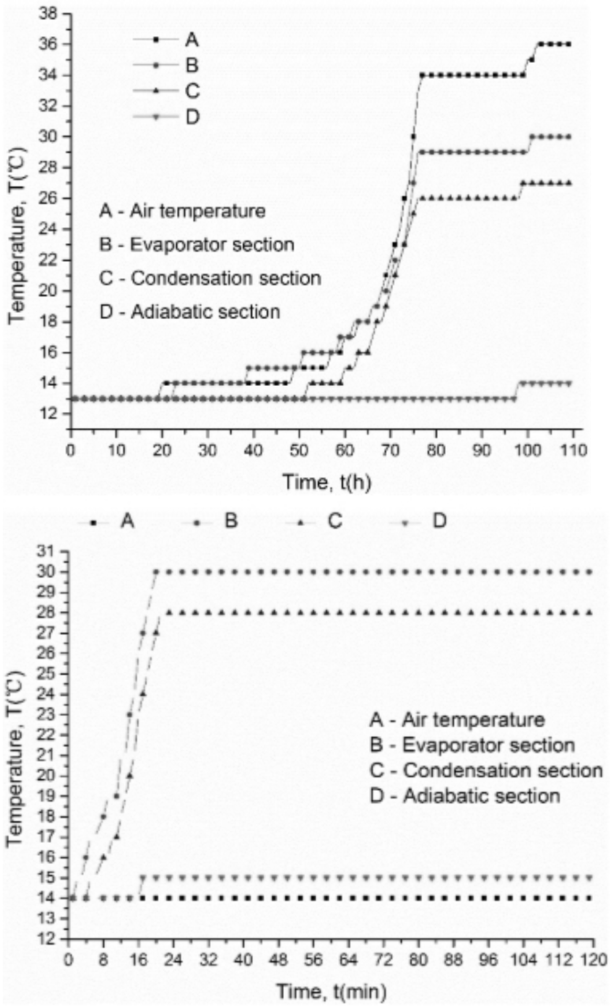

Fig. 2. Startup characteristics of the heat pipe after 110 h and 120 min

of the study are as follows:

The paper theoretically verified the feasibility of the thermoelectric conversion device to power low power wireless sensors.

A thermoelectric conversion device was designed that could be applied in a forest in future.

The thermoelectric conversion device was then manufactured. The device consists of a heat pipe, thermoelectric electronic generator, copper sleeves, and endothermic fins. The components of the device were designed to take on special shape to optimize the functioning of the device.

The thermoelectric conversion device produces 298.5 mV for the temperature difference of 20 °C. This is sufficient meet the demands of a forest wireless sensor. The

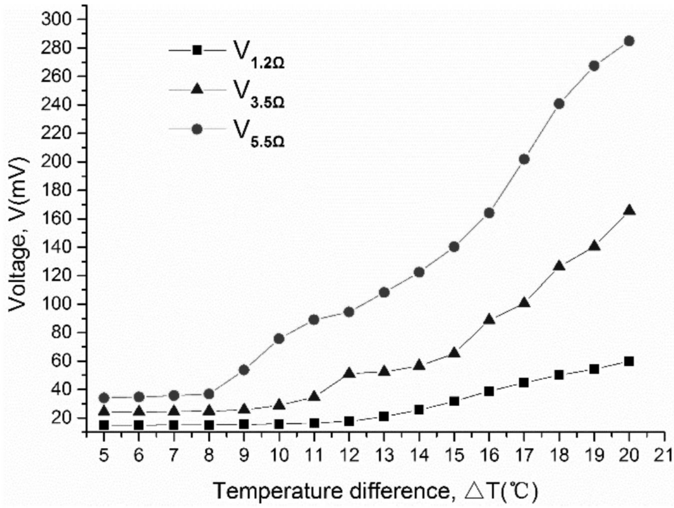

Fig. 3. Voltage as a function of the temperature difference ($\Delta T \uparrow$)

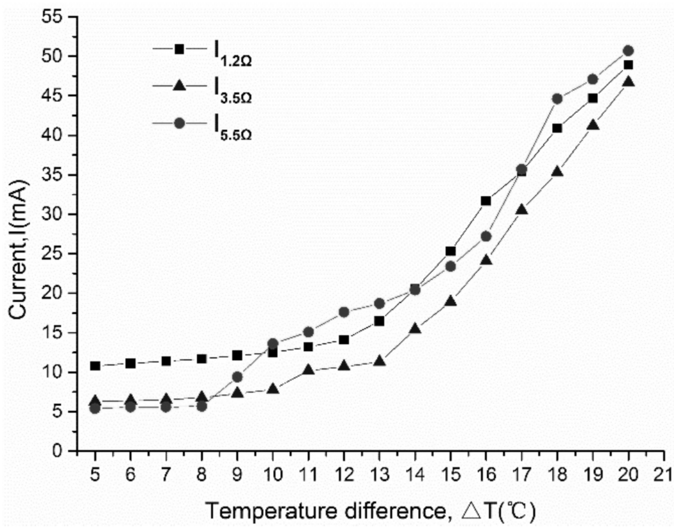

Fig. 4. Current as a function of the temperature difference ($\Delta T \uparrow$

results of this study will thus contribute towards future application of thermoelectric generators in forests.

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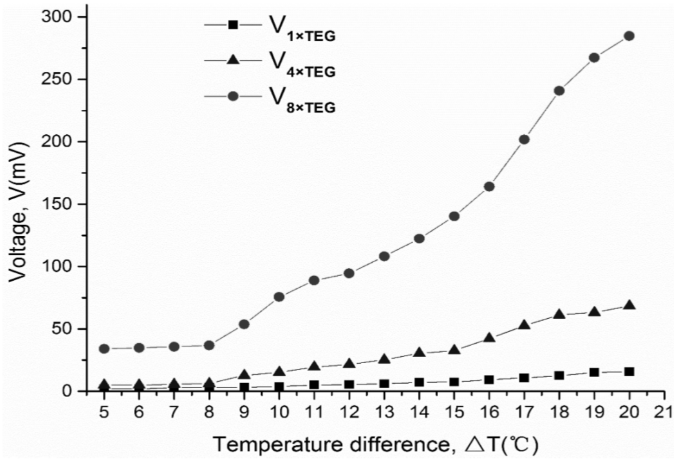

Fig. 5. Voltage changes with different TEGs

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