WASTE HEAT RECOVERY FOR HYBRID ELECTRIC VEHICLES USING THERMOELECTRIC GENERATION SYSTEM

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Abstract:

Thermal energy can be easily converted to electrical energy using the thermal electric generator (TEG). This paper is aimed to developing a model of TEG array for Hybrid Electric Vehicle (HEV) system. The proposed system is implemented experimentally by increasing the temperature difference between the two sides of TEG array. To achieve the high temperature difference between these sides, the hot side is putting on the exhaust manifold of car, and the other side is colded by using the air-condition system in the car. The voltage generated from TEG is used for achieving maximum energy to recharge a battery car. Simulation results are carried out using MATLAB/Simulink software package to investigate the system performance. The experimental results are presented to demonstrate the effectiveness of the proposed array of TEG for HEV system. Also, the obtained results prove that the designed array of TEG gives good performance for different operating conditions.

Keywords: Thermoelectric power generation, Charger control, Battery, Diesel Engine, Temperature Sensor.

1. Introduction

Currently, commercial availability of alternative drive systems that use electrical energy or hydrogen as primary power source is increasing in personal motor transport. However, due to the current high costs of required technologies and deficits of the infrastructure, in recent decades, awareness of sustainability and the protection of the environment have increased significantly.

Temperature distribution and heat flow in the exhaust system of diesel engine to pinpoint technical parameters of the system for heat retrieval and changing of thermal energy into electric energy was presented. Temperature of exhaust gases as well as geometric and material lineaments of exhaust system were the input data accepted for modeling [1].

TEGs can improve the net power exhaustion of electronic parcel by generating power from the chip waste heat [2]. Moreover, the rapid developing of power electronics technologies has even rational high energy-effective vehicles [3].Transient heat assigned compute in automotive exhaust systems are increasingly hired in the design and optimization phases. The current status of knowing related heat transfer externals in automotive exhaust systems are abridges in paper [4].

The thermodynamic models of the united system are developed in MATLAB/Simulink ambience with temperature dependent material properties and analyzed for variable operating temperatures. It has been institute that, in the irreversible thermodynamic model of the combined system with MPP, when the hot and cold side of TEG and TEC are preserved at a temperature difference of 150 K and 10 K respectively, the power output of TEG increases from 20.49W to 43.92 W, cooling power of TEC increasingly from 32.66W to 46.51W and the overall combined system efficiency increases from 2.606% to 4.375% respectively when compared with the irreversible combined system without MPPT [5].

Quality of TEG depends on parameters such as the type of electrical current applied to the junction the p-type and n-type semiconductor, the temperature of the hot and cold thermal conductivity and electrical heating elements, and thermal resistance of the TEG heat sinking [6].

The internal combustion engine is of fundamental important for individual mobility. The request for internal combustion engines increases in relation to inhabitance growth and fuel consuming. At present, mohair drive concepts using bearable energies only play a secondary role in mobility. The TEG can be minus CO_2 as internal combustion engine (ICE) consumes to drive the alternator, which stocked the necessary electrical power [7].

In this paper TEG array is designed and modeled for HEV system. The temperature difference between the two sides of TEG array is achieved experimentally in the laboratory. The high temperature is achieved by putting the hot side on the exhaust manifold car while the cold side is exposed to the air conditioning system of the car. The TEG generated voltage is used to recharge a car battery for achieving maximum energy. Simulation results are investigated to demonstrate the validity of the design array of TEG for HEV applications. The performance of the proposed system which is obtained experimentally have a good agreement with a simulation results.

2.Modeling of Thermoelectric Generation TEG System

Thermoelectric Generation is a device that converts high thermal energy directly to maximum electrical power. Thermocouple is the basic unit of TEG which consists of p-type and n-type pellet pairs of interrelated metal. The arrays of thermocouples that are electrically connected in a series are usually composed to increase the operating and thermal voltage in parallel to reduce the thermal resistance, and between the ceramic heat exchanger arrays are located on both ends respectively to expand the uniform thermal as shown in **Fig. 1**. One side of the slide has less temperature than the other, so the cold side of the TEG is cooled. While the other side of the slide has a high temperature, therefore, it is called the hot side of the TEG [8, 9, and 10].

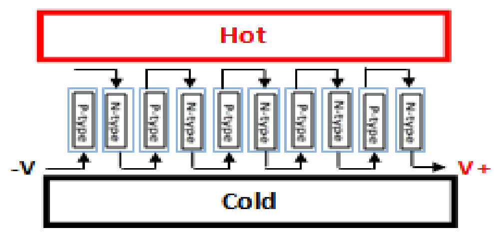


Fig. 1 Schematic diagram of thermoelectric couples in a TEG

Seebeck effect, which is the base of TEG, states that an electromotive force is introduced between two semiconductors when a temperature difference exists [11]. The open-circuit thermoelectric potential V_{OC} is obtained from the following equation;

$$Voc = \alpha \times (Th - Tc) = \alpha \times \Delta T \qquad (1)$$

Where T_h and T_c are the temperatures of the hot and cold sides; (°C)

α is the See beck coefficients.(V/°C);

ΔT is the temperature difference across the two junctions;

The Seebeck coefficient of the junction between two materials is the difference between the two absolute coefficients and experimental data show that metals' See beck coefficients are very small [12]. Another physical effect called Peltier effect which states that if a direct current passes through a circuit of dissimilar materials, one junction will be cooled and the other will be heated. This is the reversed See beck effect and it is also polarized in that if the direction of current flow is reversed, dissipation locations and heat absorption are also reversed. Peltier heating can be interpreted as being due to the change in the average kinetic energy value of a charge carrier when it crosses a junction. The Peltier coefficient is defined as;

$$\pi = \frac{P_P}{I} \qquad (2)$$

Where P_P is the heat-transfer rate from the junction; I is the direct current owing in the circuit.

The Peltier coefficient gives the magnitude of the cooling or heating that occurs at a junction of two dissimilar materials. Thomson effect states that there is reversible absorption or liberation of heat (in excess of the Joule dissipation I^2R) in a homogeneous material simultaneously exposed to a thermal gradient under the passage of an electric current. The heat absorbed by the conductor when the current flows toward the higher temperature is:

$$P_T = \tau I \Delta T \qquad (3)$$

Where τ is the Thomson coefficient.

Both the Seebeck and Peltier coefficients are defined for junctions between two conductors, while the Thomson coefficient is a property of a single conductor. Thus the See beck and Peltier coefficients can only be determined for pairs of materials whereas the Thomson coefficient is directly measurable for individual material.

The Peltier coefficient is linked to the Seebeck coefficient by the following relationship:

$$\pi = \alpha T_j \qquad (4)$$

Where T_j is the temperatures of the junction.

From equations (2) and (4) the heat transfer rate can be expressed as

$$P_p = \alpha I T_j \qquad (5)$$

Joule effect is a physical process of heat dissipation in a resistance element (R_{teg}). The flow of electric current through the TEG will additionally cause resistive heating of the thermocouples [13].This effect is observed in both sides at different temperatures but with the same amount of energy as follows:

$$P_j = 0.5 I^2 R_{teg} \qquad (6)$$

By applying the concept of energy equilibrium for steady-state analysis at both sides of the TEG, the absorbed heat generated by the thermal load and the liberated heat removed by the heat sink can be respectively given as [14]:

$$Q_h = \alpha I_{teg} T_h - k_{tc} \Delta T - 0.5 I_{teg}^2 R_{teg} \qquad (7)$$

and $$Q_c = \alpha I_{teg} T_c - k_{tc} \Delta T - 0.5 I_{teg}^2 R_{teg} \qquad (8)$$

Where k_{tc} is the thermal conductivity

The electrical power is equal to the difference between heat flow at the cold side and heat flow at the hot side [14]:

$$P_{teg} = Q_h - Q_c = \alpha (T_h - T_c) I_{teg} - I_{teg}^2 R_{teg} = (\alpha \Delta T - I_{teg} R_{teg}) I_{teg} = V_{teg} I_{teg} \qquad (9)$$

From the electrical circuit point of view, the terminal voltage of the TEG νteg is simplified as;

$$V_{teg} = V_{Ocb} - R_{teg} \times I_{teg} \qquad (10)$$

Where R_{teg} is the electrical resistance of TEG, and I_{teg} is the electric current of TEG. Note that both V_{oc} and R_{teg} are highly dependent on temperature difference.

The regular parameters in the datasheet of commercial TEGs include: T_{cold} ,T_h, the cold-side and hot-side temperatures; P_m, the power at the load matched to the internal resistance ($R_L = R_{teg}$); and Vmis the load voltage at the matched load. Obviously, one can easily calculate the electrical parameters of the equivalent circuit directly from the datasheet. The electrical internal resistance Rteg and the See beck coefficient α of a TEG can be expressed as;

$$R_{teg} = R_L = \frac{Vm}{Iteg} \quad (11)$$

$$\alpha = \frac{2Vm}{\Delta T} \quad (12)$$

3. Classification of Vehicles and its Application

Vehicles can be classified into three groups: internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV) and all- electric vehicles (AEV). **Fig. 2** shows all available vehicle types. All the detailed definitions of vehicles will be discussed next, currently being sold in Europe, is a micro-HEV .This motivate the authors to concern the study of HEV type performance with different application in this paper.

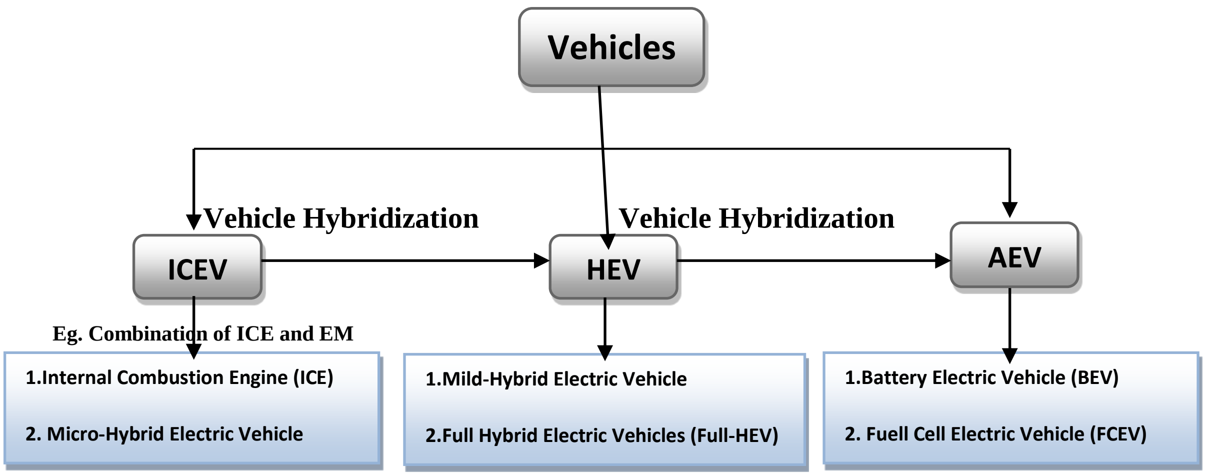


Fig. 2 The classification of the vehicle

3.1 Hybrid electric vehicle (HEV)

Now a day, there are six types of drive trains architectures for HEV which are shown in **Fig. 3**. Mild HEV has the same advantage with micro HEV but electric motor in mild HEV has an electric power of 712 KW with 150V operating voltage and can run the car together with ICE. It cannot, however, run without ICE (primary power) because they share the same shaft as shown in **Fig.3 (a).** This type of configuration normally gains fuel efficiency up to 30% and can reduce the size of ICE [15]. Today, most of the carmaker shave the same pace to produce full HEV due to it sues of split power path either running go just ICE or the EM, or both. Without compromising the driving performance, full HEV can save as much as 40% of fuel. Normally, this type of HEV has high capacity energy storage system (ESS) they are more flexible on their control strategies than the other two configuration -s. Nonetheless, the major challenge is that they need precise control strategy. Furthermore, full--HEV configuration offers the lowest cost and the option of using existing manufacturer methods for engine, batteries and motors [15]. Toyota Prius, Toyota Auris, Lexus LS 600h, Lexus CT 200h and Nissan Tino are commercially available series–parallel full-HEV while Honda Insight, Honda Civic Hybrid and Ford Escape are commercially available parallel full-HEV . However, the plug-in hybrid electric vehicle (PHEV) is similar to full-HEV but the battery can be plugged in to grid. Actually, PHEV is directly transformed from any type of HEV. For instance, **Fig. 3 (f)** shows series–parallel HEV transforming into PHEV by adding charger beside the battery. So during running, the driver can set the power draw from battery pack more instead of ICE where it is one of the strategies to further improve the vehicle performance. For instance, in urban drive or a short distance drive, the driver could select the electric motor mode in order to achieve fuel efficiency as compared to the use of ICE engine. This strategy makes PHEV suitable both in city driving and highway driving pattern [3].

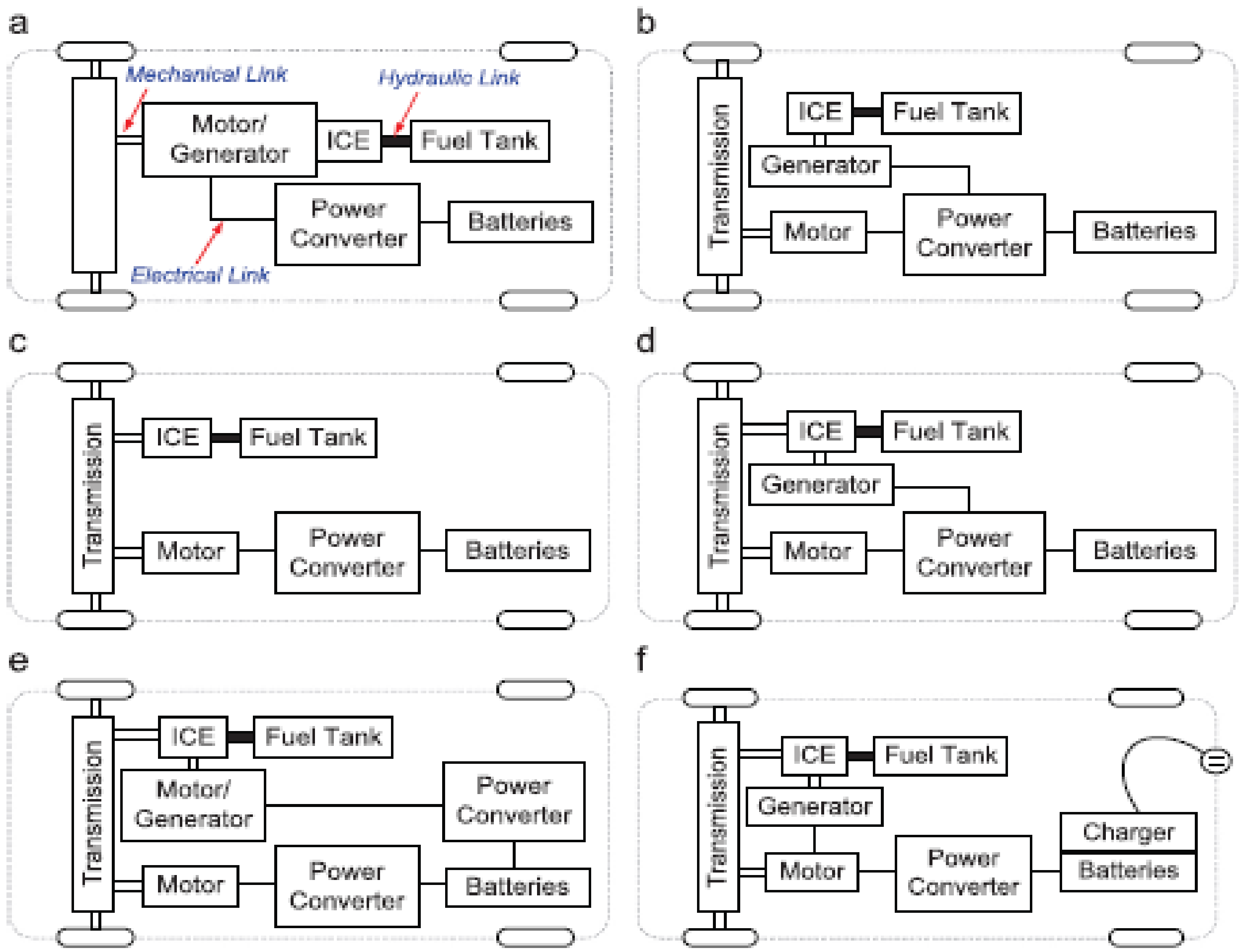


Fig.3 The drive trains architectures on HEV: (a) mild-HEV,(b) series full-HEV, (c) parallel full-HEV,(d) series-parallel full-HEV, (e) complex full-HEV, (f) series-parallel PHE [3].

3.1.1 HEV based on battery

Battery is a storage device which consists of one or more electrochemical cells that convert the stored chemical energy into electrical energy. There are several characteristics that one should take into account in selecting the most appropriate battery for EV. The most sign if can characteristics the battery capacity, which is measured in ampere hours (Ah). Besides that, the energy stored in battery (capacity average voltage during is charge) which is measured in watt hours (Wh) should be carefully calculated. The useable state-of-charge (SOC) of the battery which is represented in percentage is equally important as it indicates the current status of charge available in the battery [3].

3.1.2 HEV based on DC-DC Converters

TEMs are connected to the on-board power supply through DC-DC converters in order to link the recovered electric power to the load. The physical principle of a DC-DC converter is to charge and to discharge electric storage elements like inductors or capacitors. The duration of the charging and discharging is controlled through electric switching elements, Fig. 4 shows the categorization of DC-DC converter types [6].

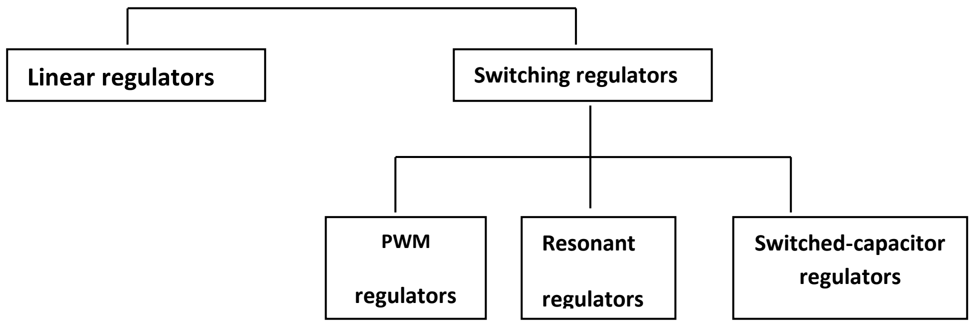


Fig.4 Categorization of DC-DC converters [6].

4. Experimental work

4.1 Experimental set-up

This car (Internal Combustion Engine**)** is equipped in the experiment and supplied it with gasoline and tested the engine without load, The temperature measuring device to the exhaust combustion engine to know the degree of temperature instantaneously, A suitable tray them dimensions is selected [20 cm * 10 cm] ,then we put the chip TEG in the empty box on the other side touching the engine and making entrance for the flow of water inside and another to expel water from it, We installed the tray on the engine with a cold solder, The TEG chip matrix is connected to the multimeter, We connected the water whom outlet from the car radiator of the motor cooling cycle, The results did not give enough cooling to the therefore there was no difference in temperature to generate the voltage required to charge the battery, An ice is used as a coolant for TEG slices, TEG began to give readings on the multimeter but not very enough to generate energy because of the cold solder which worked as an insulator causing the temperature not to be reached to the slides, The slides are placed directly on the engine without tray and put the snow on it as a good cooling method as **Fig 5**.

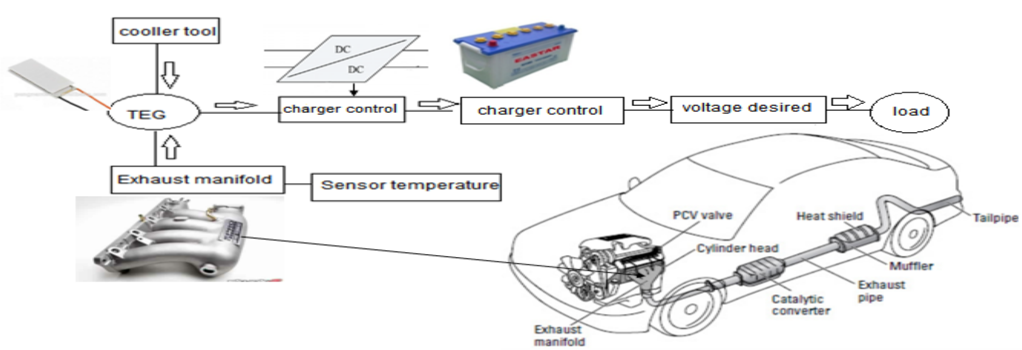


Fig. 5 Implementation of proposed system and their component

4.2 Experimental Results

The experimental results obtained in this paper is based on the implementation HEV system shown in **Fig. 5** by putting constant load resistance (R_L=0.6 ohm) to read an acceptable output values of load voltage and current using a digital multi-meter as **Fig. 6**. The value of open circuit voltages and short circuit currents are measured experimentally based on the proposed implementation system of **Fig. 6** at different values of hot and cold temperatures. Also, the values of load currents and voltages are measured in the laboratory at constant values of load resistance (R_L=0.6 Ω) and different values hot and cold temperatures. All measured result which are obtained experimentally at different operating conditions are listed in table 1.

Table.1: The measured results obtained experimentally

The Temperature (° C)		Short circuit current Is.c (A)	Open circuit output voltage Vo.c (V)	The Ampere (A) (with load current) R = 0.6 Ω	The Voltage (V) (with load voltage) R = 0.6 Ω
T_h	T_C				
50° C	0° C (by ice)	16.68 A	3.858 V	4.78 A	2.87 V
90° C	3° C (by water)	24.74 A	5.413 V	6.61 A	3.96 V
100° C	5° C	26.5 A	5.911 V	7.18 A	4.30 V
150° C	15° C	34.43 A	8.4 V	9.95 A	5.97 V
200° C	20° C	42.55 A	11.21 V	12.9 A	7.78 V
215° C	22° C	44.61 A	12.01 V	13.8 A	8.29 V
300° C	25° C	57.04 A	17.11 V	19.0 A	11.41 V

From these results, the values of circuit voltages and circuit currents in all cases (open circuit, short circuit and load conditions) are increased significantly with the temperature difference two junctions.

5. Simulation Results

The digital simulation results are obtained based on system the module of TEG (1–12611–6.0). The simulation was carried out to demonstrate the variation of short circuit current and open circuit voltage with the variation of hot and cold temperature using MATLAB/Simulink soft package program .The MATLAB/Simulink program for the proposed system model under study is simulated as shown in Fig.7.

Fig. 6 Experimental set-up

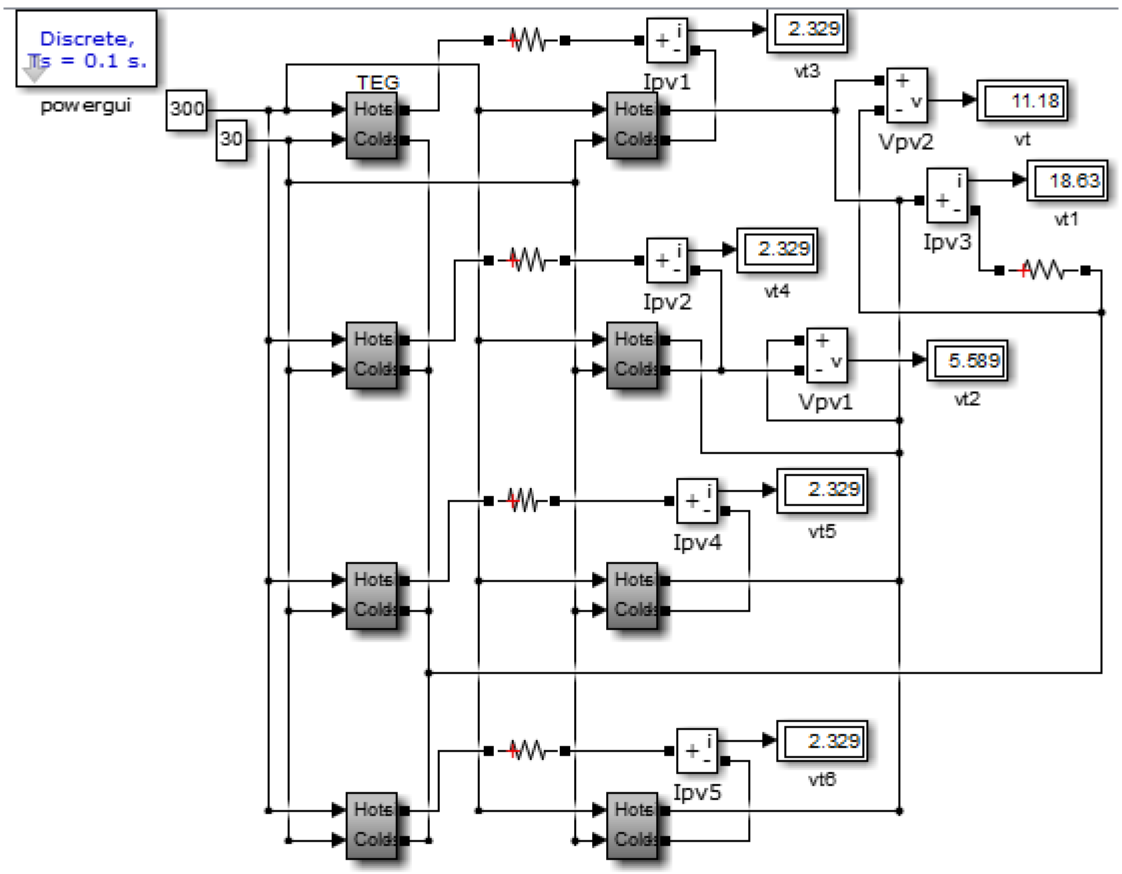
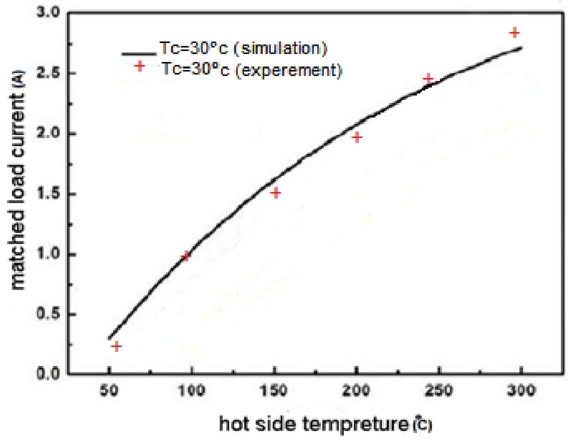


Fig. 7 Representation of TEG array connection model using MATLAB/ Simulink program

Fig. 8 and 9 show the variation of short circuit current and open circuit voltage values with the different temperature across the two junctions. From these figures, it will be noted that, the values of short circuit currents and open circuit voltage are approximately increased linearly with the different temperature across the two junctions. The values of generated output voltage and power are measured experimentally for comparison purposes as shown in Fig. 10. Also, The measured values of output voltage and power are agreed with the simulated one. This figure shows the measured voltage have small difference with simulated one is due to the difference between actual value of internal resistance and its nominal value. The maximum output power is occurred when the values of load resistance approach to the internal resistance of the TEG (matching condition) at 2.9A as shown in Fig. 10.



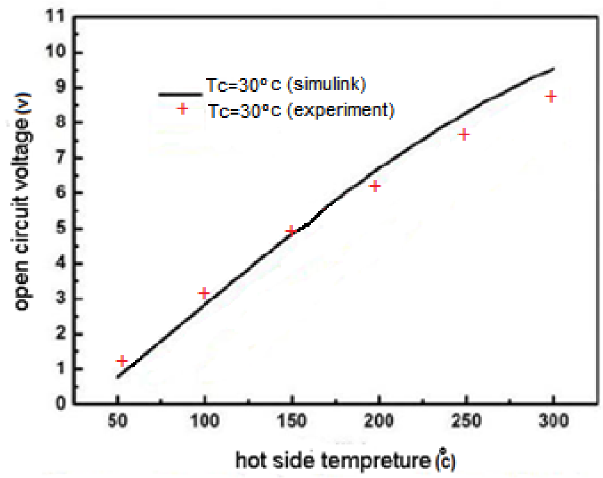


Fig. 8 :Open circuit voltage at two faces of comparison

Fig. 9: Matched load current at two faces of comparison junction

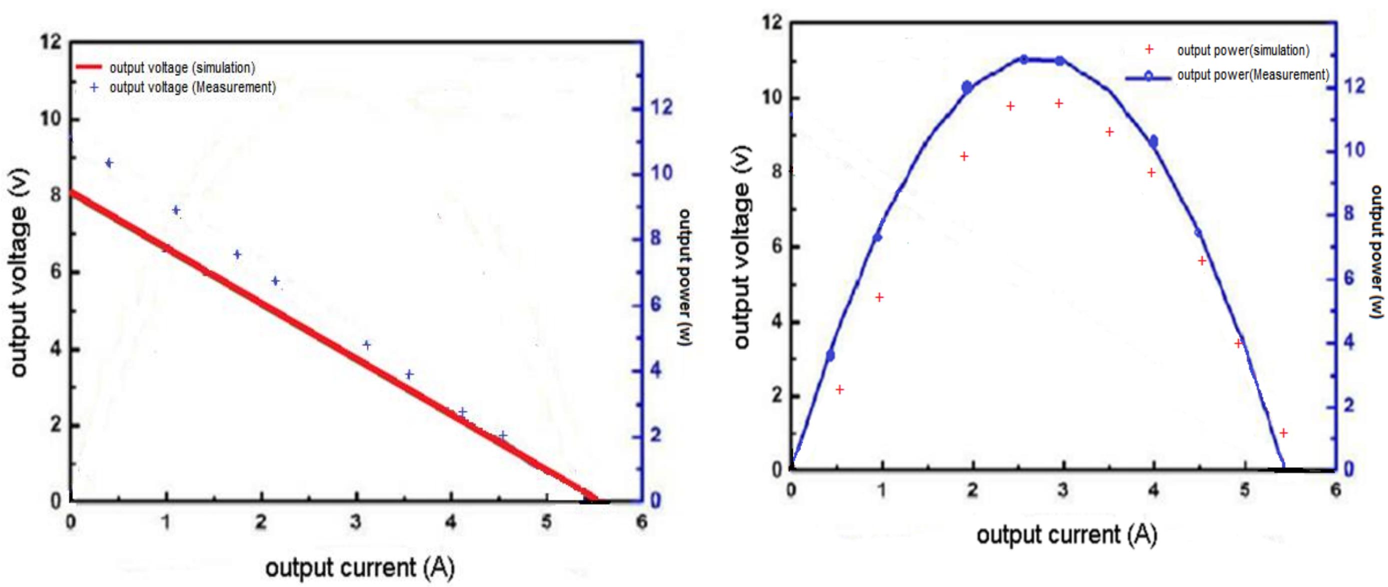


Fig. 10: Output voltage, power and current at two faces of comparison

6.Conclusion

This paper is aimed at developing a mathematical thermal model of TEG array for HEV system. The array of TEG is designed to achieve maximum energy to recharge the battery for driving HEV. Digital simulation of the thermal power model of TEG is using MATLAB / Simulink software package. This paper also, includes an experimental set-up to implement the array of TEG system at different operating conditions. The measured values of open circuit voltages and short circuit currents obtained experimentally at different temperatures are agreed satisfactory with the simulated one. The values of load voltages and currents which are obtained experimentally have agreement compared to the simulated one for matching load. Also, the output generated power is measured experimentally and has a good agreement with simulated one.

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ملخص المقالة

تهدف هذه المقاله الى تطوير نظام حرارى رياضى لمولد كهروحرارى يستخدم فى انظمة السيارات الهجينة. حيث انه تم تصميم مصفوفة من شرائح المولد الكهروحراريلتحقيق اقصى قدرة ممكنة لاعادة شحن بطارية السيارة. تم تصميم برامج محاكاة باستخدام الماتلاب وكذلك تم عمل اجراء الاجزاء العمليه لقياس الفولت والتيار الناتج من هذه المصفوفة تحت ظروف تشغيلية مختلفة وتحت تاثير درجات حرارة مختلفة وذلك للحصول على اقصى قدرة ممكنة وتم مقارنة النتائج العملية بالنتائج من برامج المحاكاة وحصل توافق كبير بين هذة النتائج. ومن هذة النتائج يمكن الاستفادة من الحرارة المفقودة الناتجة من محرك السيارة فى اعادة استخدامها بطريقة مثلى لاعادة شحن بطارية السيارة عن طريق النموذج المقترح.