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Generation of Electricity from Gasoline Engine Waste Heat

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Abstract
A typical total waste heat recovering technology, using thermoelectric generators (TEGs), coupled with a gasoline engine was investigated in this study. Mathematical methods for assessing and optimizing the performance of the application were presented followed by the different configurations of the applications of TEGs in vehicles. The test rig, set up in an indoor experimental laboratory, was a Cussons gasoline engine with energy recovering at the front, middle and rear of the exhaust gas pipe and at the exit of the water cooling pipe. Experiments were performed under both idle and loading conditions of the engine. Though the overall efficiency of the TEGs was low due to high irreversibilities, the output power of the TEGs established a level of electrical power that can be obtained from the engine waste heat.
Key words: Gasoline engine, waste heat, TEGs, electricity.

1: Introduction

Exhaust heat is a byproduct of a number of everyday devices, such as cars, stoves, fireplaces, furnaces, ovens, boilers, kilns and clothes dryers. The exhaust gas from these devices is usually set free into the air where its energy dissipates into the atmosphere increasing global warming. About 50% - 85% of the overall energy loss in a combustion engine is heat which is either carried away by the vehicle's radiator or blown out with the exhaust gases [1, 2]. The heat which is carried off by the vehicle's radiator and that of the exhaust pipe is never put into use again and is therefore called waste heat. Even if a small fraction of the waste heat could be turned into useful energy again it would be a step in the right direction of improving engine economy and meeting other sundry requirements in vehicles. Engineers have found effective technology that maximizes energy efficiency and minimizes carbon emission by harnessing or recycling the energy contained in the waste heat [3, 4]. Available waste heat in automotive exhaust gas and engine cooling water can be utilized by converting it to electricity using thermoelectric generators (TEGs).

Automotive thermoelectric generator (ATEG) allows the automobile to generate electricity from the engine's thermal energy rather than using mechanical energy to power an electric generator or alternator [3, 4]. Therefore, the automobile releases less heat and fewer emissions, and therefore lowers global warming and pollution [2, 5, 6]. The ATEG's ability to generate electricity without moving parts is an advantage over mechanical electric generators or alternators [1]. Attachment of ATEG could ultimately increase the fuel economy by up to 4% because the waste heat is used to generate extra voltage which can be used to power the vehicle's electrical components, such as the headlights [7]. ATEG's use in vehicles can enhance the lifespan of battery since part of the electricity demand of the vehicle will be supplied by the ATEG. The battery power can be made smaller for the same electrical power demand; subsequently this enhances cost saving and enables more flexible packaging of the battery [8]. Besides, TEG can electrify accessories and decouple them from that which is provided by the battery; when used as thermoelectric air-conditioner can reduce energy used in automotive conventional heating, ventilation and air-conditioning's (HVAC) by up to 50% and absence of the conventional HVAC system will eliminate all toxic, greenhouse and flammable gases associated with automotive HVAC [6, 9, 10]. It also advantageous in that TEG's use matches power demand to real time need; enables the use of alternative electric power sources and beltless electric motor can be used with higher reliable faster variable speed since friction associated with mechanical drive will be eliminated [11]. Availability of lower cost high efficiency thermoelectric modules will enable cost-effective direct conversion of waste heat to electricity thereby improving energy efficiency of vehicles, where internal combustion engines (ICEs) with TEGs are used.

Although the Seebeck effect, on which TEG works, was discovered in 1821, the use of TEGs was restricted mainly to military and space applications until the second half of the twentieth century [12, 13]. This restriction was caused by the low conversion efficiency of thermoelectric materials at that time. In 1963, the first TEG was built and reported by Neild [12]. Birkholz et al [14] published the results of their work in collaboration

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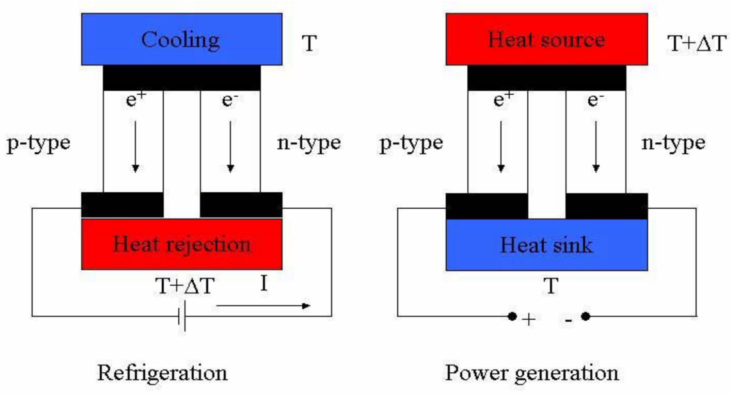
with Porsche. These results described an exhaust-based ATEG which integrated iron-based thermoelectric materials between a carbon steel hot-side heat exchanger and an aluminium cold-side heat exchanger. This ATEG could produce tens of watts out of a Porsche 944 exhaust system as was carried out by Haidar and Ghojel [15]. In the early 1990s, Hi-Z Inc designed an ATEG which could produce 1 kW electricity from a diesel truck exhaust system [7, 13, 16]. The company in the following years introduced other designs for diesel trucks as well as military vehicles. In the late 1990s, Nissan Motors published the results of its ATEG which utilized silicon germanium (SiGe) thermoelectric materials. Nissan ATEG produced 35.6 W in testing conditions similar to running conditions of a 3.0 litres gasoline engine in hill-climb mode at 60.0 km/h [17]. Clarkson University in collaboration with General Electric Motor has designed an ATEG for a Sierra pick-up truck and the published literature of this ATEG explained its ability to produce 255 W at a vehicle speed of 112 km/h [18, 19]. In 2006, scientists in BMW of North America announced their intention to launch the first commercial ATEG in 2013 [20]. The ATEG, providing power to drive thermoelectric air-conditioner (TEA) in vehicle is more efficient and serviceable [18]. The TEA obtained with ATEG with no belts, valves, hoses (refrigerant lines), compressor and refrigerant is more reliable [19].

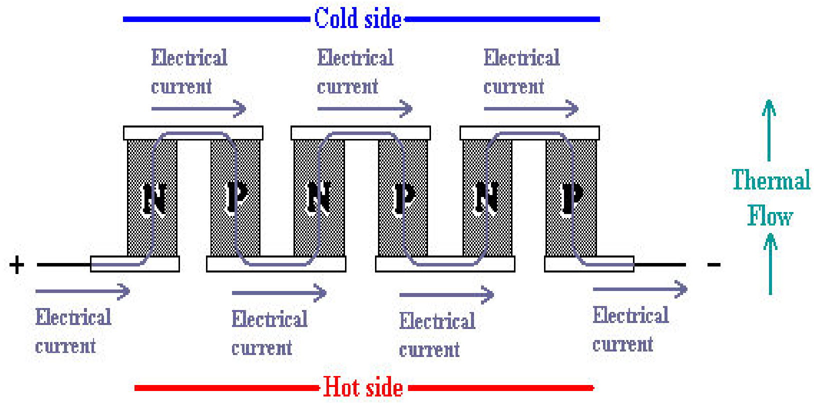
The number of papers and conferences being held in recent times to discuss the applications of ATEG shows that the technology has come of age [1, 8, 21]. This paper discusses the design formulae to assess the performance of the TE applications in automotive engine and then presents the different configurations put in place to use TEGs in internal combustion engines (ICEs). A typical total waste heat energy recovery technology with a Cusson laboratory gasoline engine test rig with TEGs coupled to it, under idle and running conditions of the engine, is investigated. The concluding sections deal with the presentation of the experimental tests results

2: Principles and Analysis of ATEG

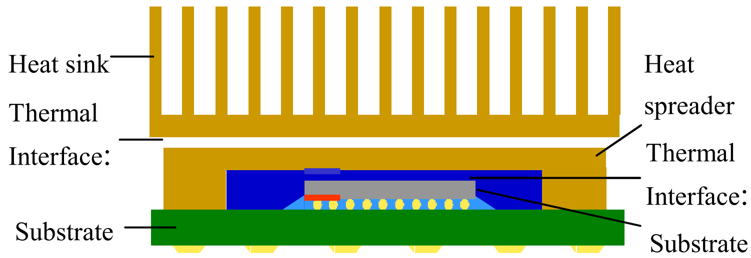
As is illustrated in Figure 1a (i), when heat is absorbed on one side of an ATEG (red arrow) the movable charge carriers begin to diffuse, resulting in a uniform concentration distribution in the ATEG along the temperature gradient, and producing the difference in the electrical potential on both sides of the ATEG (Seebeck's generator). To maximize the power generation output, p-bars and n-bars (see circles) are connected together in a cell. Due to the thermoelectric effect, electrons flow through the n-type element to the cold side while in the p-type elements, the positive charge carriers flow to the cold side. This illustrates how connecting the p-bar and the n-bar augments the voltage of each bar and the voltage of each unit cell. These unit cells are assembled in long sequences to eventually build a TEG as shown in Figure 1a (ii and iii).



(i) Operation of



(ii) Elements are combined in series to increase voltage and power output



(iii)

Figure 1a: Thermoelectric Device

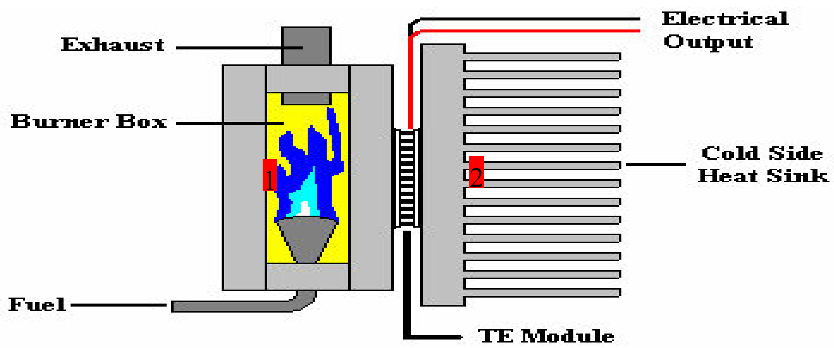
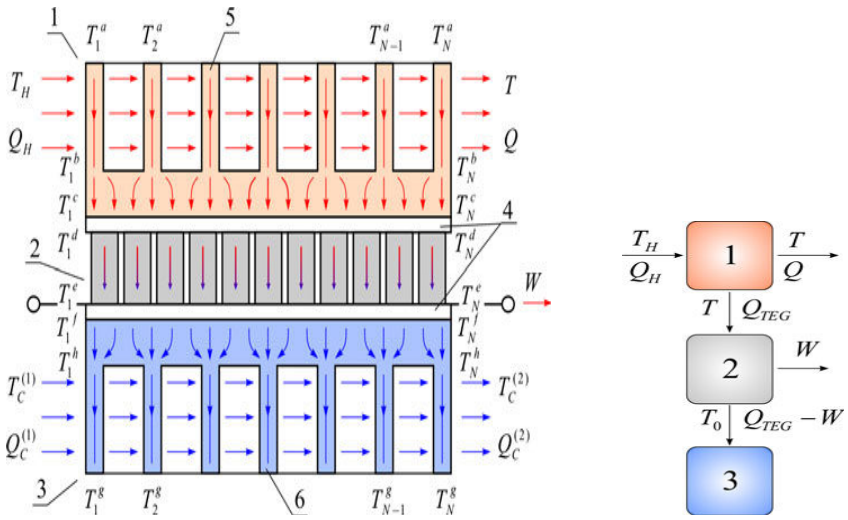


Figure 1b: Thermoelectric Generator (TEG)

Figure 1b shows a TEG utilizing the exhaust gas heat for operation. Interestingly enough, the thermodynamic principle can be reversed; by forcing voltage through an ATEG, a cooling effect (Peltier cooler) is achieved. Vapour compression based refrigeration systems in the automobile could be replaced with such higher efficiency, solid-state Peltier coolers. With exhaust temperatures of 700°C or more, the temperature difference between exhaust gas on the hot side and coolant on the cold side is several hundred degrees. This temperature difference is capable of generating 100-500W of electricity. In the water coolant based system, though the temperature is lower, it may be high enough to produce significant electricity for use in the vehicle when TEGs are attached.

Figure 2 shows both the physical and computational models. In it, 1 represents a hot heat exchanger (whereby thermal energy of exhaust gas is transferred to thermoelectric modules), 2 represents thermoelectric modules (whereby heat from the modules is carried away by either liquid or air), and 3 is a thermostat whose temperature is kept constant at T_0. In so doing, the temperature T of gases leaving the hot heat exchanger is equal to the hot temperature of the modules of the TEG. From the hot heat exchanger, heat (Q_{TEG}) is transferred to modules 2 and thermostat 3. Ignoring also heat loss to the environment (the generator is well thermally isolated), based on the law of conservation of energy; the heat that goes to thermostat will be Q_{TEG}-W, where W is the electric energy received from the modules. One should also take into account the thermal resistances 4 between the module and heat exchanger. It can be assumed, for generality, that heat exchanger 1 is a gas or hot water operated. The heat exchanger surfaces can be extended by means of elements 5 and 6 in the form of fins, pins, hollow cylinders, etc., used to increase heat-transfer coefficient of the heat exchangers. Gas flow at temperature (T_h) with thermal energy (Q_h), enters heat exchanger 1 and leaves it at pipe temperature (T) with reduced thermal energy (Q). In the radiator system, the subscript of the temperature and energy are interchanged. Because of the inevitable fluid mixing, it can be assumed that the temperature of outgoing fluid is uniform. The difference in thermal flow, $Q_h - Q$, is transferred to modules 2.



Physical Model Computational Model

Figure 2: Modeling of the Thermoelectric Generator.

Neglecting temperature losses in the heat exchangers and assuming a constant specific capacity for the gas and water with the use of such a model can give the largest efficiency that should be sought in the construction of generator embodiments. Thermal power input to the generator by the exhaust gases is equal to:

$$Q_h = mc(T_h - T) \qquad (1)$$

where Q_h is heat of the thermoelectric module (TEM); m, mass of radiator water or exhaust gas, c specific heat capacity of the fluid; T_h is the surface temperature of inner shell of TE module, T is the exhaust pipe temperature. Part of this energy is transferred by the thermoelectric converter modules and the remaining part leaves the generator together with the exhaust gas or hot water. Therefore, energy released in the thermoelectric equipment, Q_{TE} is:

$$Q_{TE} = mc(T - T_c) \qquad (2)$$

where T_c is the TEM cold side temperature.

The generator efficiency, η is found from the expression:

$$\eta = \frac{\dot{W}}{\dot{Q}_{TE}} \qquad (3)$$

where η is the ratio of the electric power output ($\dot{W}$) to the thermal power input ($\dot{Q}_{TE}$).

The efficiency of an ATEG is governed by the thermoelectric conversion efficiency of the materials and the thermal efficiency of the two heat exchangers and as long as the thermal power input does not all flow through the thermoelectric converter, this efficiency is lowered. The generator efficiency with regard to module efficiency can be written as [22-24]:

$$\eta_{ov} = \eta_{conv} \times \eta_{TE} \times \varepsilon \qquad (4)$$

where η_{ov} is the overall efficiency of the ATEG, η_{conv} is the conversion efficiency of thermoelectric materials, η_{TE} is the efficiency of the heat exchangers and ε is the ratio between the heat passed through thermoelectric materials to that passed from the hot side to the cold side. Expressed thermodynamically, the efficiency of a thermoelectric equipment (TE) device is the amount of electrical power generated, P_{elec} for a given amount of heat input, P_h; $\eta_{TE}=P_{elec}/P_h$. This efficiency can be calculated as a function of the hot-side temperature, T_h, the cold-side temperature, T_c and dimensionless figure of merit, ZT_m as [25- 27]:

$$COP_{gen} = \eta_{TE}.\frac{Q_{TE}}{Q_h} = COP_C\left[\frac{\sqrt{1+ZT_m}-1}{\sqrt{1+ZT_m}+\frac{T_h}{T_c}}\right]\frac{Q_{TE}}{Q_h} \tag{5}$$

where $COP_C=(T_h-T_c)/T_c$ is the Carnot COP , $\eta_{TE} = COP_C\left[\frac{\sqrt{1+ZT_m}-1}{\sqrt{1+ZT_m}+\frac{T_h}{T_c}}\right]$ and

$ZT_m = \frac{\alpha^2\sigma}{k}T_m = \frac{\alpha^2\sigma}{(k_p+k_n)}T_m = \frac{\alpha^2}{k\rho}\frac{(T_c+T_h)}{2} = \frac{\sigma\frac{\Delta V}{\Delta T}}{k}T_m$ = 1.2 to 1.8 with 1.6 as viable figure; $T_m=1/2(T_h+T_c)$ is the average temperature of the TE module, Δv, voltage change, ΔT, temperature change and COP is co-efficient of performance and COP_{gen} is co-efficient of performance of the TEM.

Let the dimensions of single generators approach the infinitely small distance, dx. The temperature difference in a module of such a single generator is equal to $T_{(x)}-T_0$, where T(x) is temperature at distance x. The equation must be solved with the boundary conditions $T(0)=t_h=T_h-T_0$ and $T(L)=t_c=T-T_0$; T_o is the atmospheric temperature. Therefore, at ambient temperature, the figure of merit, Z_0 is:

$$Z_o = \frac{\alpha^2\sigma}{k} = \frac{\alpha^2}{Rk} = \frac{\alpha^2}{\left[(\rho_n k_n)^{\frac{1}{2}} + (\rho_p k_p)^{\frac{1}{2}}\right]^2}$$

$$= \frac{(\sigma_p - \sigma_n)^2}{\left[(\rho_n k_n)^{\frac{1}{2}} + (\rho_p k_p)^{\frac{1}{2}}\right]^2} \tag{6}$$

where α, Seebeck's coefficient (V/K); ρ, resistance (ohms) of the semiconductors; σ, electrical conductivity; K_p; material thermal conductivity for p-type and n type semi-conductor and R, resistance, in Ω of the system.

Let us introduce a variable, $t(x)=T_{(x)}-T_0$, then, the work output from the TEM is:

$W=-mcZ_o\int_{t_h}^{t_c} t\,dt = mcZ_o\frac{t_h^2-t_c^2}{2}$ and $Q = cmt_h$:

$$\eta_{TE} = \frac{\dot{W}}{\dot{Q}} = Z_o\frac{t_h^2-t_c^2}{2t_h} \tag{7}$$

$$COP_{generator} = Z_o \frac{t_h^2 - t_c^2}{2t_h} \cdot \frac{Q_{TE}}{Q_h} \quad (8)$$

where $\dot{W}$ in Watts is the electricity generated.

In generators with such an exponential temperature distribution along the modules, it is not reasonable to use low-temperature modules. In generators, through use of a number of thermal converters and heat exchangers connected in series in a heat carrier circuit, one can expect a factor of improvement of efficiency as compared with the maximum efficiency of a generator where the hot surfaces of the modules are at equal optimal temperatures. With the use of identical thermal converters of equal thermal conductivity, the temperature distribution between the hot plates of the modules must be exponential.

The main challenge in improving thermoelectric materials is that the three relevant properties (electrical conductivity, thermal conductivity, and Seebeck coefficient) are interrelated. The equation dictates that one must maximize ZT. T_c increases ZT and requires a material that is highly electrically conductive, but thermally insulative, with a large α. Z is a direct measure of the cooling performance of a thermoelectric module. Z is temperature dependent though, so, when comparing one module to another, they must be based on the same hot-side temperatures.

The magnitude of the difference between the thermo-powers of the two materials is directly proportional to the Seebeck's coefficient of the junction. In a physical sense, the Seebeck's coefficient can be thought of as the amount of energy each electron carries across the junction relative to the Fermi energy. To find the most efficient thermoelectric generating device, it is necessary to optimize each material's figure of merit, making Z as large as possible. This is a difficult task since the thermo-power, electrical conductivity, and thermal conductivity are each determined by the specific electronic structure of the material; it is not possible to change one parameter without changing the others.

The TEG's optimum geometry couple has COP or ZT which is [25, 26]:

$$ZT = \frac{mT - \frac{m^2}{2} - \frac{T - T_c}{Z}}{m(T - T_c) + m^2} \quad (9)$$

where m=IR/S . The optimum co-efficient of performance of the TEG, COP_{opt} is given as:

$$COP_{opt} = \frac{\frac{1}{2} ZT_c^2 - (T - T_c)}{ZTT_c} \quad (10)$$

T_c is about 80^0C and T is about 700^0C.

The COP of N-stages (N>1) thermoelectric generating system can be expressed in the following form, assuming that each stage operates over a temperature difference of (T- T_c)/N for N number of modules [25, 26]:

$$\eta_n = \frac{1}{(1 + \frac{1}{\eta'})^N - 1} \quad (11a)$$

where η' is the COP of a single-stage module and

$$\eta' = n(\eta_1 + \frac{1}{2}) - \frac{1}{2} \quad (11b)$$

Here, η_1 is the coefficient of performance for a single-stage Seebeck module that operates over a temperature difference of (T-T_c)/N. For example, the COP of a 2-stage module is:

$$\eta_{12} = \eta_1 + \frac{1}{8(2\eta_1 + 1)} \quad (11c)$$

and the COP of a 3-stage module is

$$\eta_3 = \eta_1 + \frac{(2\eta_1 + 1)}{27\eta_1^2 + 27\eta_1 + 7} \qquad (11d)$$

The total efficiency of the generator can be defined as in equation (4).

3.1: Irreversibility Analysis in TEG

There exists, therefore, an optimum heat sink design derived from the balance between the reduction in the plate-to-plate thermal conductance and the TE module's operation at a larger difference in temperature. The basis for the optimization of the heat sink is the minimization of the irreversibility or generation of entropy. In effect, the design that uses an optimized heat sink will need less power to achieve a given set of heat pumping conditions than designs using non-optimized heat sink. Thus, a significant difference in temperature (large dT) is also needed to generate sufficient electrical energy.

The nature of the effort to minimize the entropy generation (irreversibility) can be seen by examining the following equation. The operating entropy generation, $S_{gen,}$ equation is as follows [28-33]:

$$S_{gen} = \frac{ds}{dt} - \sum \frac{Q}{T} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \qquad (12a)$$

Certain assumptions are made regarding the use of entropy in modeling a TE system:

- The system is at steady state and hence, the rate of entropy change, ds/dt =0. However, the rate of entropy accumulation tends to a maximum as the temperature tends to a maximum.
- Heat transfer through a heat sink occurs solely from the sink interface to the sink-TE module interface.
- The heat and cold sink plates are isothermal.
- The heat sink footprint matches the TE module footprint.

Equation (12a) can be applied to the heat sink particulars as in Figure 2 and then reduces to the following by substituting the parameter of heat flow under conduction using Fourier's law [28]:

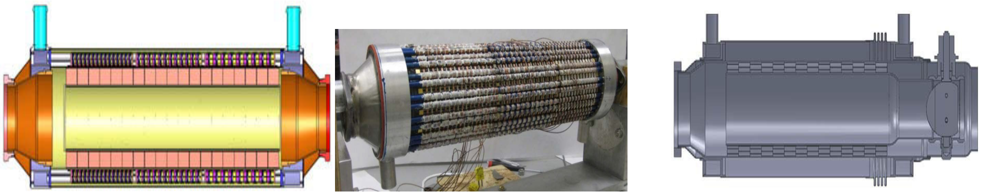
$$S_{gen} = \frac{\left(\dot{Q}_h - \dot{Q}_c\right)}{\frac{kA(T_h - T_c)}{L}} \qquad (12b)$$

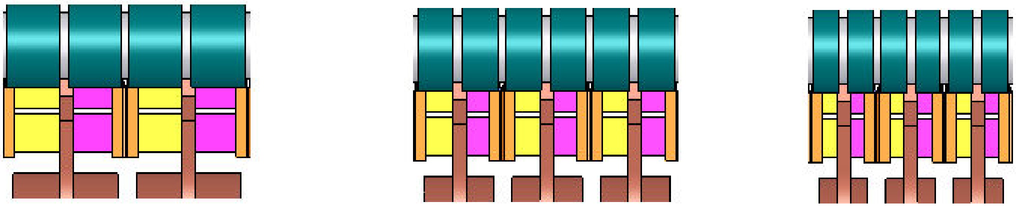
where A is the area of the TEM, $\dot{Q}_h$, is the TEG power input; $\dot{Q}_c$ TEG power output, T_h is TE hot side temperature, T_c is TE cold side temperature and L, is the length of TE. The loss represented by equation (12b) is the imperfection in the system and anything done to reduce it will enhance and therefore optimizes the performance of the system.

3: Materials and Method

A typical ATEG consists of four main elements: A hot-side heat exchanger, a cold-side heat exchanger, thermoelectric materials, and a coupled assembly system. ATEGs can be classified into two categories depending on their hot-side heat exchanger: exhaust gas-based and water coolant-based. The exhaust gas-based ATEGs convert the waste heat from the exhaust gas in an internal combustion engine into electricity. Also, water coolant-based ATEGs uses the engine coolant's waste heat to generate electricity. The coupled assembly system is such that the thermal contact resistance between the thermoelectric module of the TEG and the heat exchanger surfaces is reduced. In water coolant-based ATEG, the energy is extracted from the hot water out of the engine, while in the exhaust gas-based ATEG, the energy is extracted from the waste exhausted gas. This study considers energy recovering from both categories.

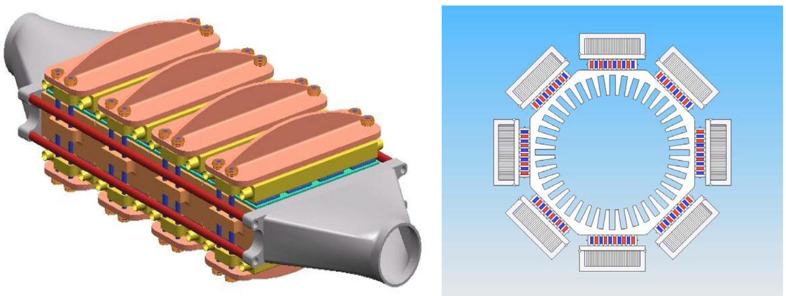
Figures 3 to 4 illustrate the different configurations of the applications of TEGs. Figure 3a shows the attachment of the TEGs at the various points in the engine exhaust gas pipe. In Figure 3b, the type used for the exhaust gas system is shown (i) while the type used in the water cooling system is shown in (ii).





At the Front | At the Middle | At the Rear

Figure 3a: TEGs' Configuration along Exhaust Gas Pipe



(i) Pictorial View (ii) Cross-sectional View

Figure 3b: TEGs' Octagonal Cross- Section

Figures 4a, 4b and 4c illustrate a total energy recovery ATEG, modified total energy recovery ATEG line diagram and a completely TEG driven motor vehicle respectively. The concept involved in Figure 4a is adopted in this study.

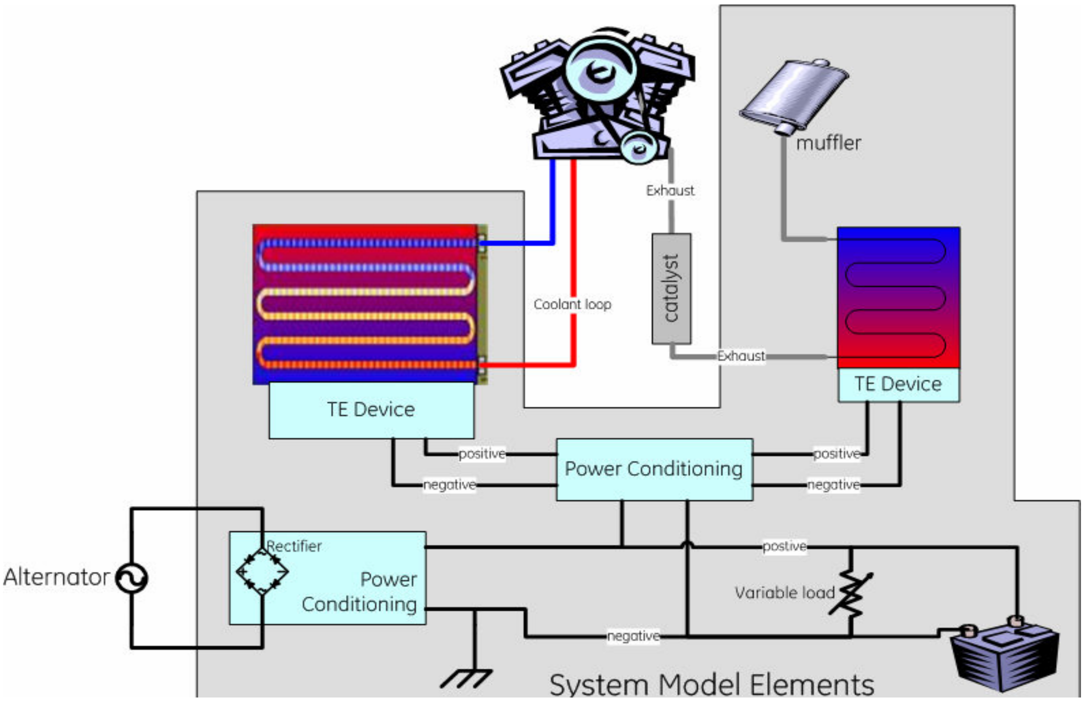
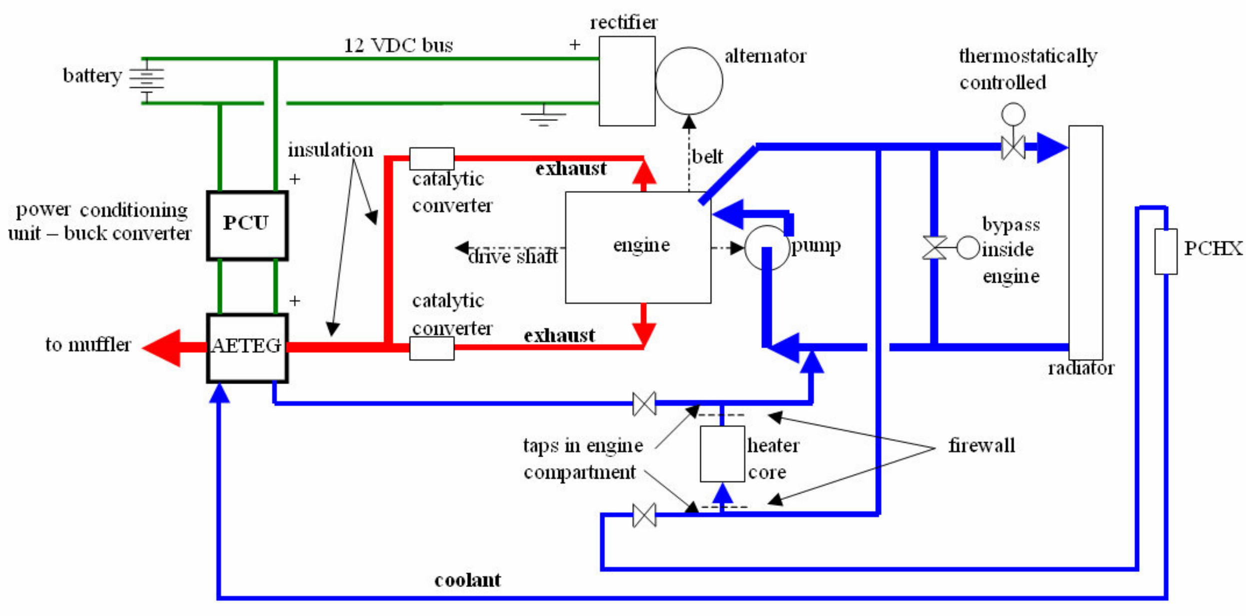


Figure 4a: A Total Energy Recovery ATEG



Systems: Exhaust Coolant Electrical

Figure 4a: A Modified Total Energy Recovery ATEG Line Diagram

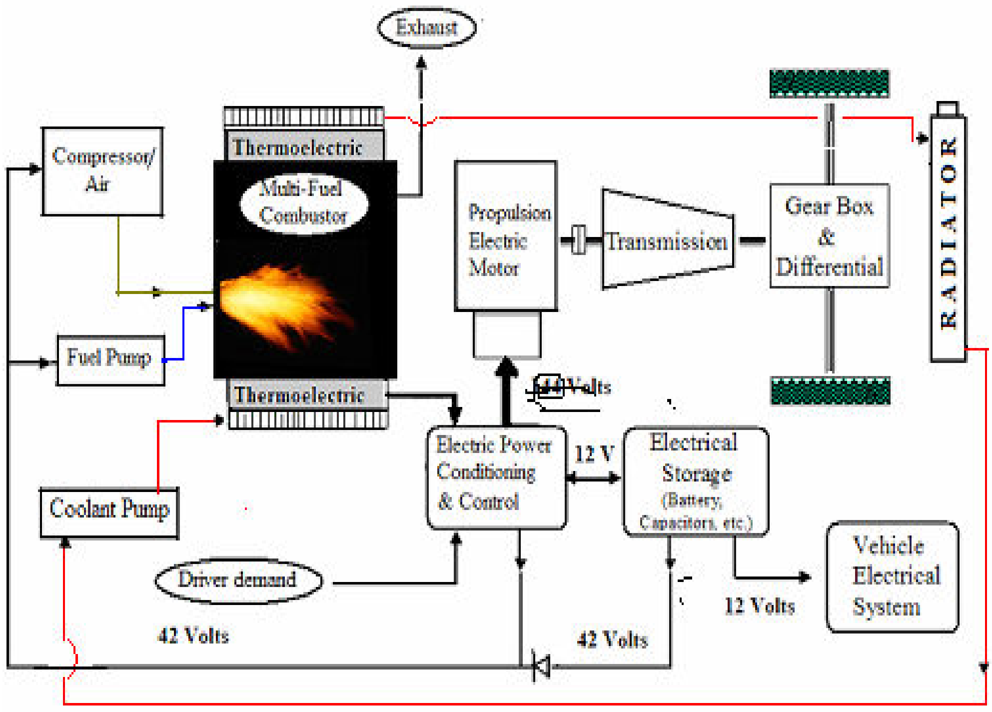


Figure 4c: A Completely TEG Driven Motor Vehicle

The test bed as shown in Figure 5a is a Cussons P8650 series data logged multi-cylinder automotive engine test beds, which have been developed to provide a self contained facility for the practical demonstration of internal combustion engine technology, but TEGs now coupled to it. The test bed is arranged to include a manual engine throttle and adjustment of the excitation applied to the alternator, which acts together to provide complete and efficient control of the engine speed and load. An emergency stop push button is also provided. A number of instrumentation is provided which includes engine manifold vacuum gauge, engine charging circuit ammeter, hours run indicator, air flow meter - orifice plate and sloping manometer, fuel flow meter - twin bulb burette, speed indicator (digital with analogue trend) and load indicator (digital with analogue trend). The temperature indication include ten way indicator and type K thermocouples for air inlet, fuel, engine coolant inlet and outlet, lubricating oil, exhaust manifold, exhaust gas inlet and outlet to calorimeter, and coolant inlet and outlet to calorimeter.

The exhaust is short, but the compartment allows TEs to be attached at three different positions (see Figure 5b) using the arrangement in Figure 3a and the components in Figure 3b. The engine cooling package is installed at the front of the test stand using water/water heat exchangers controlled via automatic thermostatic valves for regulation of the engines coolant system. For the purpose of this study, the hot water outlet rubber hose from the engine is replaced by steel metal hose (see Figure 5c) on which three set of TEs are attached. The coolant system is fully sealed enabling conventional automotive vehicle based pressurised operation to be achieved. Figure 6 shows the line diagram of the ATEG showing the fluid pathway.

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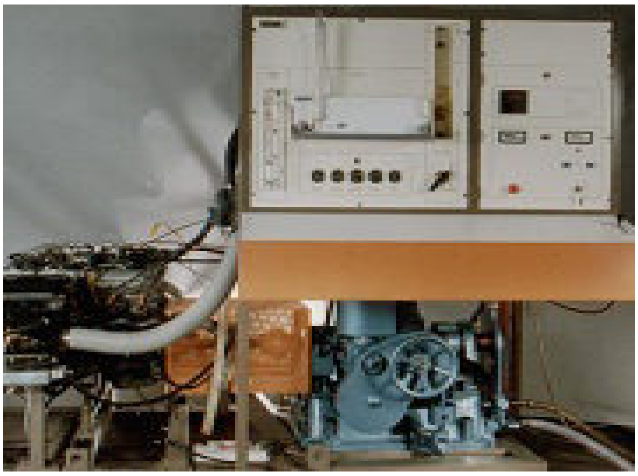
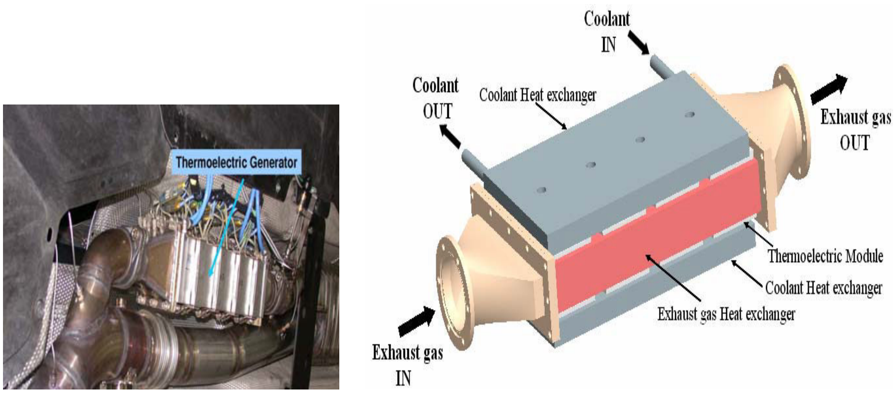


(a) Cusson P8650 Series Engine Test Rig



(ii) **TEGs' Along Exhaust Gas Pipe**

(iii) TEGs' Along Water Radiator Outlet Pipe

Figure 5: Cusson Engine Test Rig Showing Exhaust Gas and Exhaust Water TEGs

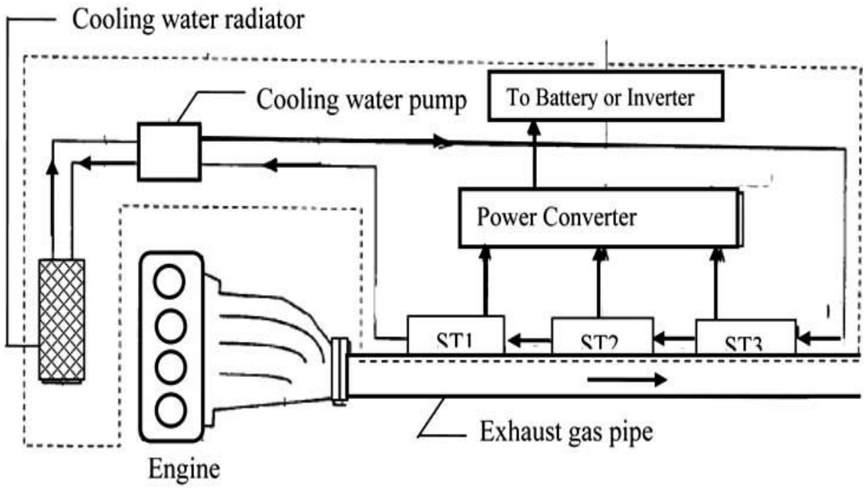


Figure 6: A Total Energy Recovery ATEG Showing the Fluid Pathway

In this heat recovery situation that is under investigation, it is essential to know the amount of heat recoverable and how it can be used. Understanding the process of the ATEG is essential for the development of waste heat recovery in vehicle using TEGs. Advanced type thermoelectric modules based on SiGe and Bi_2Te_3 have been developed to apply it to gasoline engine vehicles [34-37]. The size of the module used in this study is 12 mm square and 8 mm in height. The module consists of 8 couples of p- and n-type Si-Ge elements. Twenty four (24) modules are arranged between exhaust gas pipe with a rectangular cross section and 8 octagonal cross-section attached to the radiator water exit pipe from the engine. Thus, a thermoelectric generator has been made using 32 modules, with 8 each at the front, middle and rear of the exhaust gas pipe. At each section, four modules each are electrically connected in series to sum up the voltages and the current of the system is double by having the four modules connected to the other four in parallel using Molybdenum electrodes by brazing method. The maximum electric power expected from the module is approximately 22W, at the temperature difference of 500 K between hot and cold sides of the module. Also expected is that the generated electric power of the present generator with the 32 TEGs (i.e; 22x32) is 704W when the exhaust gas is introduced into the generator under the condition corresponding to the 80 km/h hill climb mode of 2.0 litres gasoline engine vehicle.

The actual driving condition on the road was simulated using the test engine in an indoor experimental laboratory. The experiment was performed under both idle and driving conditions of the engine.

4. Results and Discussion

The average results obtained carrying several tests on the TEG units are presented in tables 1-3 and the characteristic curves are shown figures 7-9. In the tables and figures, TEG1 TEG2 and TEG3 represents the thermoelectric generators in front, middle and rear of the engine exhaust pipe respectively while TEGw represents the thermoelectric generator at exit pipe manifold of the cooling water system of the engine. Other abbreviations used in the tables and figures are explained as follow:

$T_{in,}$ temperature of the hot water leaving the engine or of the exhaust gas before the TEG
$T_{out,}$ temperature of the water leaving the engine or of the exhaust gas after the TEG
ΔT is the temperature change
$\dot{m}$ flow rate in kg/s of exhaust water or gas
P_{shell}, electric power in Watts generated by the thermoelectric module
η_{gen} is the efficiency of the generator
U is the co-efficient of heat transfer
ΔT_{Shell} is the temperature change in a module
Volts, voltage generated
Amp, current in Ampere
Pw, power generated by each thermoelectric generator at front, middle, rear of the exhaust gas pipe and pipe manifold of the water cooling system

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Table 1: Assessment of the TEGs Application in a Gasoline Engine

ATEG	U W/m^{2}K	T_{in} ^{0}C	T_{out} ^{0}C	ΔT ^{0}C	$\dot{m}$ kg/s	P_g W	T_h ^{0}C	T_c ^{0}C	ΔT_{shell} ^{0}C	T_m ^{0}C	P_{shell} W	S_{gen} J/kgK	η_g
TEG1	0.372	700	594	106	0.02	2120	501	297	204	399.0	40.8	7.44	1.9
TEG2	0.282	580	496	84	0.02	1680	467	235	232	351.0	39.4	5.64	2.3
TEG3	0.278	455	370	85	0.02	1700	338	127	211	232.5	36.0	5.56	2.1
TEGw	0.576	20	80	60	0.30	70.6	71	42	29	56.5	3.7	17.28	5.2

η_{gen}=(121.3x100)/5570.6= 2.18%

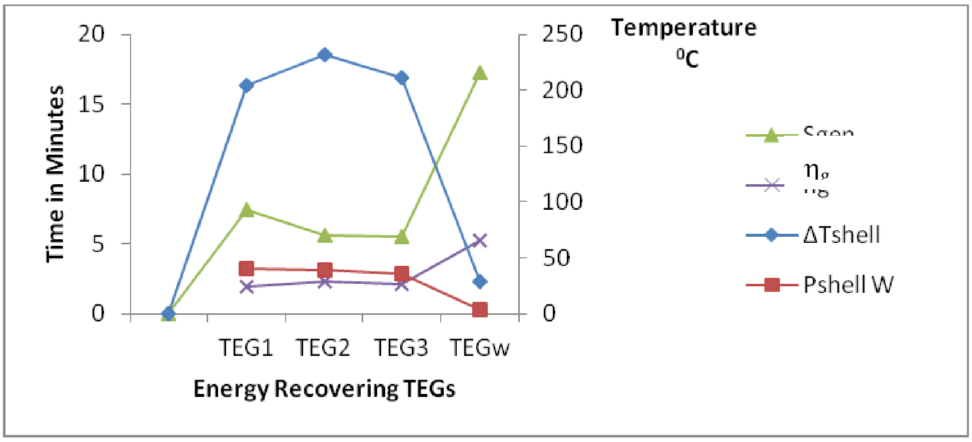

Figure 7: Electricity and Entropy Generations in TEGs of the Gasoline Engine

Table 2: Performance of the ATEG with Engine Idling

Time	TEG1	TEG2	TEG3	TEGw	Volts	Amp	Pw
1	12	11	8	8	1.1	7.0	7.70
2	23	21	19	17	1.8	6.6	11.88
3	84	76	72	67	3.7	6.2	22.94
4	112	81	70	66	4.3	5.8	24.94
5	188	122	101	87	4.4	5.3	23.32
6	201	134	121	98	4.5	5.2	23.40
7	223	143	125	101	4.6	5.1	23.46
8	231	166	131	104	4.3	5.0	21.50
9	228	154	130	103	4.4	4.8	21.12
10	243	157	134	106	4.5	4.7	21.15
11	241	165	132	111	4.6	4.5	20.70
12	251	161	137	108	4.6	4.1	18.86
13	250	162	141	113	4.7	3.8	17.86
14	251	172	140	117	4.6	3.3	15.18

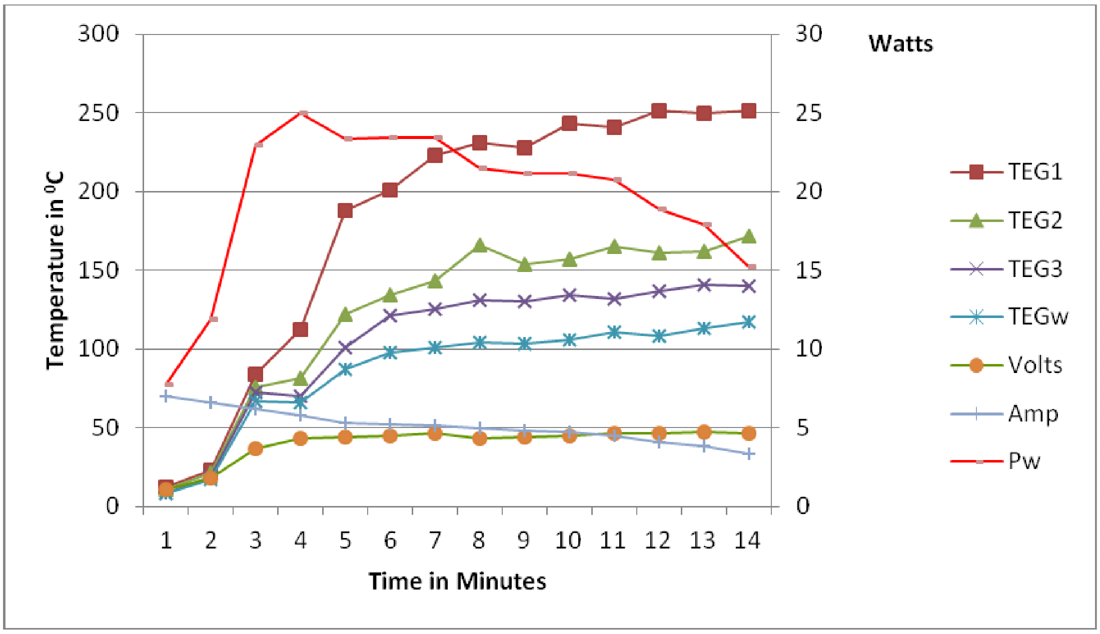

Figure 8: Performance of the ATEG with Engine Idling

Table 3: Performance of the ATEG with Engine under Loads

Time mins	TEG 1	TEG 2	TEG 3	TEG W	Volts 1	Amp 1	Volts 2	Amp 2	Volts 3	Amp 3	Volts 4	Amp 4	Total Pw
1	12	11	8	8	1.1	7	0.8	4	1.1	3.2	0.20	2.00	14.82
2	23	21	19	17	1.8	6.6	1.1	4.5	1.2	3.2	0.20	1.90	21.05
3	84	76	72	67	3.7	6.2	2.2	4.3	1.3	2.1	0.30	1.85	35.69
4	112	81	70	66	4.3	5.8	3.1	4.2	1.6	2.0	0.40	1.85	41.90
5	188	122	101	87	4.4	5.3	3.2	4.1	1.9	2.0	0.40	1.80	40.96
6	201	134	121	98	4.5	5.2	3.3	3.8	2.0	1.9	0.60	1.80	40.82
7	223	143	125	101	4.6	5.1	4.3	3.7	2.1	1.8	0.70	1.80	44.41
8	231	166	131	104	4.3	5	4.4	3.7	2.3	1.5	0.75	1.70	42.51
9	228	154	130	103	4.4	4.8	4.4	3.3	2.5	1.5	0.80	1.65	40.71
10	243	157	134	106	4.5	4.7	4.3	3.2	2.5	1.4	0.90	1.64	39.89
11	241	165	132	111	4.6	4.5	4.4	3.1	2.6	1.4	0.90	1.63	39.45
12	251	161	137	108	4.6	4.1	4.4	2.8	2.6	1.4	0.95	1.60	36.34
13	250	162	141	113	4.7	3.8	4.5	2.6	2.7	1.3	1.00	1.55	34.62
14	251	172	140	117	4.6	3.3	4.5	2.2	2.7	1.3	1.00	1.50	30.09

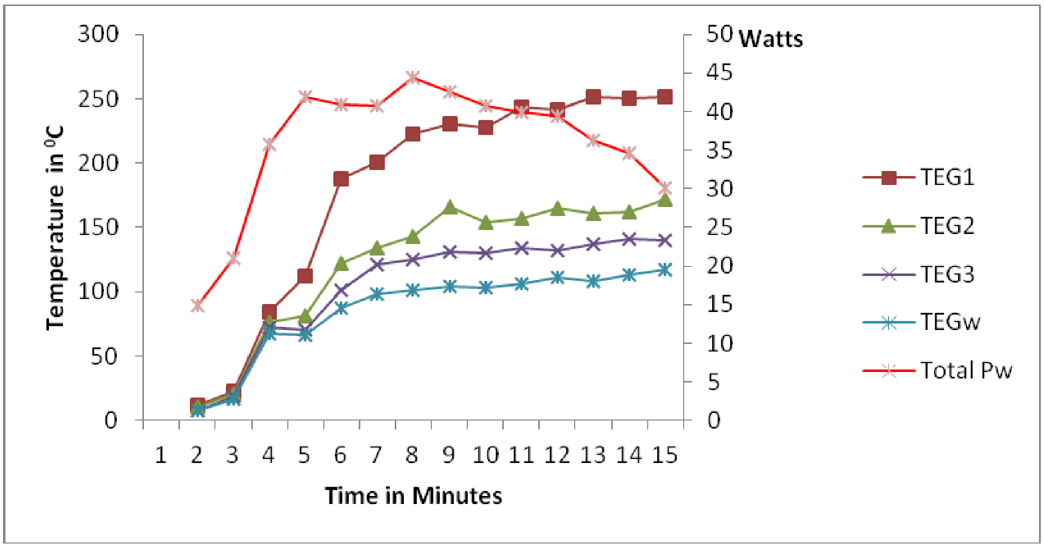

Figure 9: Performance of ATEG with Engine under Loads

The results presented in tables 1-3 and Figures 7-9 suggest conclusions that are of practical interest. As in indicated in table one, there is substantial average temperature drop for the thermoelectric generators (TEG1, TEG2 and TEG3 respectively) along the length of the exhaust pipe: 204°C for the one in the front, 232°C for the one in the middle and 211°C for the one in the rear. In the case of water coolant-based thermoelectric generator (TEGw), the average temperature drop was 29^{0}C. Table 1 also shows, looking at the amount of entropy generation (which is calculated using equation (12b)), that irreversibility is higher with water coolant-based TEG than exhaust gas-based TEG. Dividing the required electrical power by the amount of rate of the waste heat available at various points of attachment of the TEGs provides an estimate of the overall ATEG system conversion efficiency, which is η_g=2.18%, obtainable from this gasoline engine. If the number of TEGs is increased, the output power can be increased significantly, increasing the overall efficiency, though this efficiency may not be directly proportional to the number of TEGs. Figure 7 indicated that the temperature drop is highest with TEG at the middle of the exhaust gas pipe with slightly higher efficiency than the other two exhaust gas based TEGs and the corresponding entropy or irreversibility is slightly about the same with the TEG at the rear. This to be expected ass the temperature of the pipe is more uniform in this portion. The water coolant based TEG recorded the highest entropy generation indicating that the generated power is lowest though the efficiency may appear higher than the exhaust gas based TEGs. This irreversibility can be pursued further with a view to determine and reduce it where it is most predominant and therefore, maximize or optimize the system performance.

Tables 2 and 3, and figures 8 and 9 show that to obtain the maximum efficiency, a change in temperature along the generator modules must obey a power law (in this case, raised to power 2) in conformance with equations (7) and (8). There is a strong correlation between values obtained for the performance of the engine at idle and loading conditions, but the output power is less for the idle condition than when the engine is loaded as the time increases as well as the temperature. The output power of the TEGs established a level of electricity that can be obtained from the engine waste heat. As is evident in figures 8 and 9; initially when the time increases, the temperature of the waste heat increases and the corresponding power output from the TEGs increases. However, after a period of time, at the engine average speed of 80 km/h to 100km/h (3,000rev/min to 3600rev/min), an optimum power output (thermoelectric efficiency is at peak) is achieved. Then diminishing return set in and even when the engine speed continues to increase with increased exhaust gas temperature, the power output drops. This is due to increase in entropy or irreversibility, which increases with increase in thermoelectric temperature as indicated by figure 7 and explains the fact that the most challenging power generation and efficiency requirements for the TEG system will be to generate the required amount of electricity as soon as the engine obtains this economic engine speeds (80 to 100km/h). From figures 8 and 9, it is evident that maximum power can be extracted from the system exhaust gas when the TEG is located at the front region of the exhaust pipe. Power output falls off sharply along the length of the pipe and the heat loads yielded minimal power extraction at the rear of the pipe.

Measurement made, but not presented in this study, without and with the TEGs attached to the exhaust gas pipe also indicated that the temperature at which the gas finally leaves the exhaust pipe is lower with the

TEG attached, which is a benefit to be reaped from this study in the context of global warming. Not considered and therefore, not evident in this presentation, is that the improvement of figure of merit of thermoelectric device is highly required for the TEGs in engine applications.

5. Conclusion

Three exhaust gas-based TEGs and one water coolant-based TEG were used to assess the performance and feasibility of waste heat energy recovering in a gasoline engine. The experimental procedure, overall, adequately enabled the assessment of the performance of the TEG applications at various points where waste heat is released from the gasoline engine. Though the overall efficiency of the TEGs was low due to high irreversibilities, the output power of the TEGs established a level of electricity that can be obtained from the engine waste heat.

However, that the overall efficiency is only 2.18% for this case study means we still have a lot of room to regenerate electric energy from the waste heat from the engine to increase the quality of the energy recovered. The role of TEGs in reducing greenhouse gases could well be very important in the global climate scheme of things and as the TEGs systems are introduced in engines as demonstrated in this study, the number of TEGs used should result in lower temperature emission and greater availability of TEGs for an extended range of applications. It is also necessary to test the application outside a stationary engine with static loading to establish the effect of variables before much can be said of the performance of the system in motor vehicles. Also, because thermoelectric modules are inherently inefficient in terms of the material medium required for the regenerative system, an assessment has to be made to find which materials will yield the best power output and researcher can use the second law to focus on particular regions where design modifications can be made to improve and optimize the system performance.

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Appendix
Nomenclature

A area occupied by thermoelectric module (TEM)
Amp Ampere
c specific heat capacity of the fluid
COP co-efficient of performance
COP_C Carnot COP
COP_{gen} co-efficient of performance of the TEM
COP_{opt} optimum co-efficient of performance,
dT_{max} maximum temperature difference
η generator efficiency
I electric current, A;
k thermal conductivity
K_m material thermal conductivity
K_p material thermal conductivity for p-type and n type semi-conductor

K_t total thermal conductivity of thermoelectric module, W/K;
L length of thermoelectric module
m mass of radiator water or exhaust gas
N number of p-n pair of couple;
P_{elec} electrical power generated
P_h power input
P_{shell} electric power
Pw power generated by each thermoelectric device
Q_h heat of the thermoelectric module (TEM)
Q_{TE} energy released in the TE equipment
R resistance, in Ω; of the system
T exhaust pipe temperature
T(x) temperature at distance x
T_{in} temperature of the hot water leaving the engine or of the exhaust gas before the TEG
T_h surface temperature of inner shell of TE module.
T_m average temperature of the TE module
T_c surface temperature of outer shell of TE module.
T_{out} temperature of the water leaving the engine or of the exhaust gas after the TEG
U co-efficient of heat transfer
Volts voltage
W electric power output in Watts from generator
Z figure of merit, 1/K;
Z_0 figure of merit at ambient temperature
ZT dimensionless figure of merit at temperature T
ZT_m dimensionless figure of merit at average temperature
α Seebeck's coefficient , V/K;
ΔT_{Shell} temperature difference in a module
ε ratio between the heat passed through thermoelectric
η energy efficiency
η_{conv} conversion efficiency of thermoelectric materials
η_e thermoelectric conversion efficiency of the elements
η_{HE}, η_{TE} efficiency of the heat exchangers or thermoelectric equipment
η_{ov} overall efficiency of the ATEG
λ ratio of the element length L to area A
ρ resistance of the semi-conductors
σ electrical conductivity
$\dot{m}$ flow rate in kg/s
$\dot{Q}_h$ module power input
$\dot{W}$ electric power output
$\dot{Q}_c$ module power output
$\dot{Q}_{TE}$ thermoelectric equipment thermal power input
η_{gen} generator efficiency
ΔT temperature change
Δv voltage change