DEVELOPMENT OF AUTOMOTIVE THERMOELECTRIC GENERATOR (ATEG)

Thesis

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF TECHNOLOGY in

MECHATRONICS

by

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June, 2013

DECLARATION

By the P.G. (M.Tech) Student

I hereby declare that the Report of the P.G. Project Work entitled "DEVELOPMENT OF AUTOMOTIVE THERMOELECTRIC GENERATOR (ATEG)" which is being submitted to the National Institute of Technology Karnataka, Surathkal, in partial fulfillment of the requirements for the award of the Degree of **Master of Technology** in the department of **Mechanical Engineering** is a bonafide report of the work carried out by me. The material contained in this Report has not been submitted to any University or Institution for the award of any degree.

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Department of Mechanical Engineering

Place: NITK, SURATHKAL

Date : 18 June 2013

CERTIFICATE

This is to certify that the P.G. Project Work Report entitled "DEVELOPMENT OF AUTOMOTIVE THERMOELECTRIC GENERATOR (ATEG)" submitted by CHETHAN R REDDY, (Register Number: 11MC04F) as the record of the work carried out by him, is accepted as the P.G. Project Work Report submission in partial fulfilment of the requirements for the award of degree of **Master of Technology** in the Department of **Mechanical Engineering**

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- Chethan R Reddy

I would like to dedicate my thesis to *all my loved ones*.

ABSTRACT

In an Internal Combustion (IC) engine driven automobile, only a fraction of the energy input by the fuel is used for vehicle accessories and mobility (about 25%), whereas the rest of the energy is reflected in the form of heat energy in the IC engine as; (1) exhaust gases (about 40%), (2) heat being carried away by the circulating engine coolant liquid (about 30%) and (3) frictional losses (about 5%). The aim of this project is to tap this energy (which is otherwise wasted) and convert a part of it into a useful form of energy and hence increase the overall efficiency of the automobile. There are several ways to tap heat energy and convert it into electricity (useful form of energy); the most promising for automobile applications is the ThermoElectric Generator (TEG). TEGs convert temperature difference directly into electricity based on the “Seebeck effect”. They are not bulky, have no moving parts and hence are highly suitable for automobile applications. The electricity generated by the TEG can substitute/eliminate fossil fuel based electricity generated in the automobile by the alternator (existing automobiles). In automobile applications, TEG works on the temperature difference between the exhaust gases (hot side) and circulating engine coolant liquid (cold side) of an IC engine and is generally called the “Automotive ThermoElectric Generator (ATEG)”. The approach taken in this project is to model ATEG for computer simulation and the inputs to this model are given from the actual vehicle measurements. The model is built in the MATLAB/Simulink environment based on the basic physics (mathematical equations) of the system. The results indicate that the ATEG system is suitable to drive all the electrical loads in a small (< 1.4 litre engine) and midsized (between 1.4 litre and 2 litre engine) IC engine driven Automobiles. Therefore, ATEG system forms a great candidate to replace the alternator for small and midsized Automobiles. Replacing the alternator by the ATEG eliminates the load of the alternator on the IC engine and increases the overall fuel efficiency of the automobile greatly (about 4-7% depending on the IC engine and electrical demand of the car).

Keywords: Seebeck effect, ATEG, IC engine, exhaust gas, MATLAB/Simulink.

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CHAPTER 1: INTRODUCTION

1.1 Motivation & Approach

In an IC engine driven automobile, only about 25% of the energy input by the fuel (Gasoline/Petrol or Diesel or Biofuel) is used for vehicle mobility and accessories. The rest of the energy is reflected in various forms as –

- About 40% as heat energy in the exhaust gases of the IC engine.
- About 30% is reflected as heat carried away by the circulating engine coolant liquid.
- About 5% appears in the form of various frictions and minor loses.

This is pictorially represented in Figure 1.1.

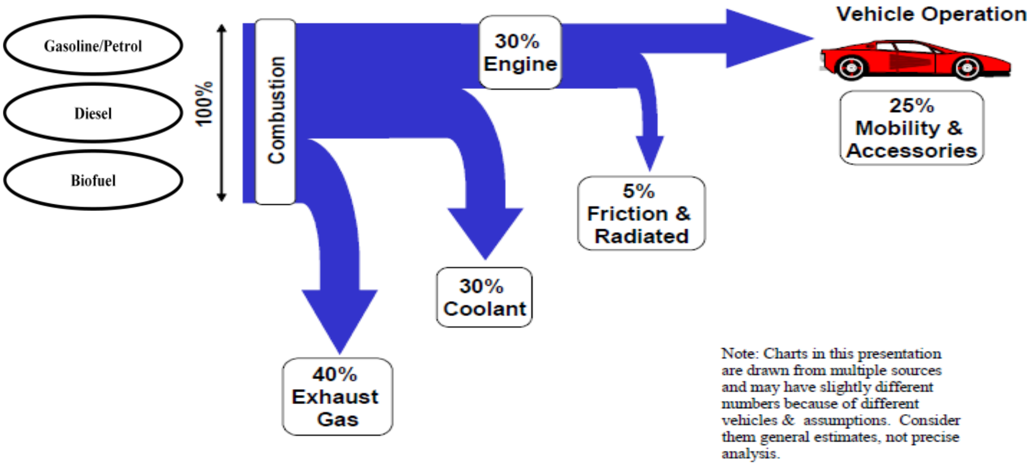

Figure 1.1: Typical energy flow path in an IC engine driven automobile. (Courtesy: Google images).

The low efficiency of IC engines, combined with the increasing environmental effects of the IC engine and the ever declining reserves of fossil fuels has triggered tremendous interest in scientists and engineers around the world to increase the efficiency of IC engines.

One novel way in this direction is to recover a part of the energy available in the exhaust gases and convert it into a useful form. This can be done by the so called Waste Heat Recovery Units (WHRUs) and the most common is a steam generator, working according to the Rankine cycle, which uses the heat from the exhaust gases, converts water to steam which drives the turbine and the turbine in turn produces electricity. But a steam turbine is bulky, has many moving mechanical parts and therefore is not suitable in an automobile, where space and volume are the main constraints. Another way to recover heat and convert it to electricity is by the use of ThermoElectric Generator (TEG), which converts temperature difference directly into electricity. TEGs work on the principle of "Seebeck effect". TEGs are not bulky and have no moving parts and therefore are highly suitable automotive applications. [Jihui Yang and Francis R. Stabler 2009].

When TEGs are applied to automobiles, they are generally called as Automotive ThermoElectric Generators (ATEG). The use of ATEG in an automobile poses many advantages, like –

- Generation of electricity which can be used to either replace alternator in an automobile, treat exhaust gases (active after treatment devices), to run auxiliary equipment and achieve higher power like supercharging or for offshore power generation.
- Implementation of ATEG to drive all the electrical loads in an automobile will eliminate the fossil fuel based electricity produced by the alternator.
- Implementation of ATEG to drive all the electrical loads in an automobile will increase the fuel efficiency of an automobile.
- Will reduce the carbon footprint of automobiles, hence will give a greener image to automobiles and increase its saleability.

In this project, the approach taken is a model based design of ATEG system. Model based design involves modeling an ATEG system for computer simulation. The modeling is done by considering the basic physics (mathematical equations) of the system. The modeling & simulation activities are carried out in MATLAB/Simulink environment. Accurately modeling a physical system and simulating it with the test inputs helps in optimizing the initial design phase and also reduces effort and cost involved in testing and designing a physical prototype in the laboratory.

1.2 Overview of Internal Combustion (IC) Engine and Electrical Demand in an Automobile

As we know IC Engines are used to drive more than 90% of the world's Automobiles. The working of an IC Engine can be summarised as follows –

1. Fresh air from the atmosphere is induced into the cylinder (either by natural aspiration or by forcing, as in supercharging etc.).
2. Air is mixed with fuel, near stoichiometric ratio, and it undergoes combustion in the cylinder (either by sparking or by compression).
3. This combustion produces torque which is used to rotate the so called crankshaft and that is used to drive the wheels by a set of gears.
4. The products of combustion appear as the Exhaust gases.

The temperature of these Exhaust gases, near to the cylinder, is upwards of 500^0C. At the nearby points of the Engine coolant liquid, which is used to cool the cylinder walls, the temperature is around 90^0C. This difference can be exploited to drive the ATEG.

The IC Engine is coupled to various devices, via belt or gears, such as the oil pump, alternator, supercharger etc. The alternator is used to charge the battery, which in turn supplies electricity to all the electrical loads of the automobile.

1.3 Project Description

The thesis involving developing of Automotive ThermoElectric Generator discusses about various aspects in the following way –

- In chapter 2, TEG's principle, operation and its adaptation to automobiles are discussed.
- In chapter 3, mathematical model of an ATEG is developed.
- In chapter 4, the inputs to the model built and results from the model are discussed.
- In chapter 5, the various control strategies required for successful implementation of ATEG are probed.
- In chapter 6, conclusion of this project work is dealt with.
- In chapter 7, the scope for the future work of ATEG and its vast business potential are discussed.

CHAPTER 2: THERMOELECTRIC GENERATOR (TEG)

2.1 Seebeck Effect

The Seebeck effect is the conversion of temperature differences directly into electricity and is named after the Baltic German physicist Thomas Johann Seebeck, who, in 1821 discovered that a compass needle would be deflected by a closed loop formed by two metals joined in two places, with a temperature difference between the junctions. This was because the metals responded differently to the temperature difference, creating a current loop and a magnetic field. Seebeck did not recognize there was an electric current involved, so he called the phenomenon the thermomagnetic effect. Danish physicist Hans Christian Orsted rectified the mistake and coined the term "thermoelectricity".

The open circuit voltage developed by a material can mathematically be described as V = S * T. [Andrew P. Freedman 2011].

Where,

V → Voltage developed across the material (V)

S → Seebeck coefficient of the material (V/K)

T → Temperature difference across the material (K)

Older TEG devices used bimetallic junctions and were bulky. More recent devices use semiconductor p-n junctions. Here, a p-type and n-type semiconductor are placed alternatively and the majority charge carriers diffuse from hot side to the cold side, resulting in a net charge flow (current) and the voltage is induced by the temperature difference in accordance to the Seebeck effect. This can be visualised in Figure 2.1.

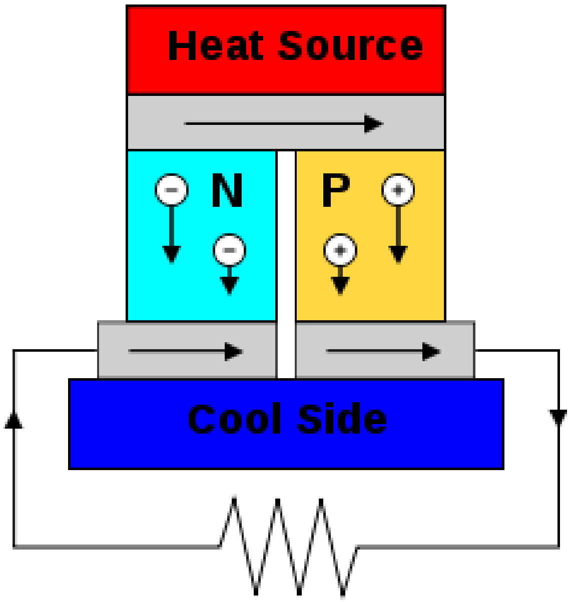

Figure 2.1: P and n type semiconductors used to achieve thermoelectric effect. (Courtesy: Google images).

2.2 Thermoelectric Module

A single thermoelectric pair (p type and n-type semiconductor connected together) produces only a few millivolts. Therefore an array of alternating p type and n type semiconductors are connected together to get a greater electrical power. A typical thermoelectric power generation module is shown in Figure 2.2.

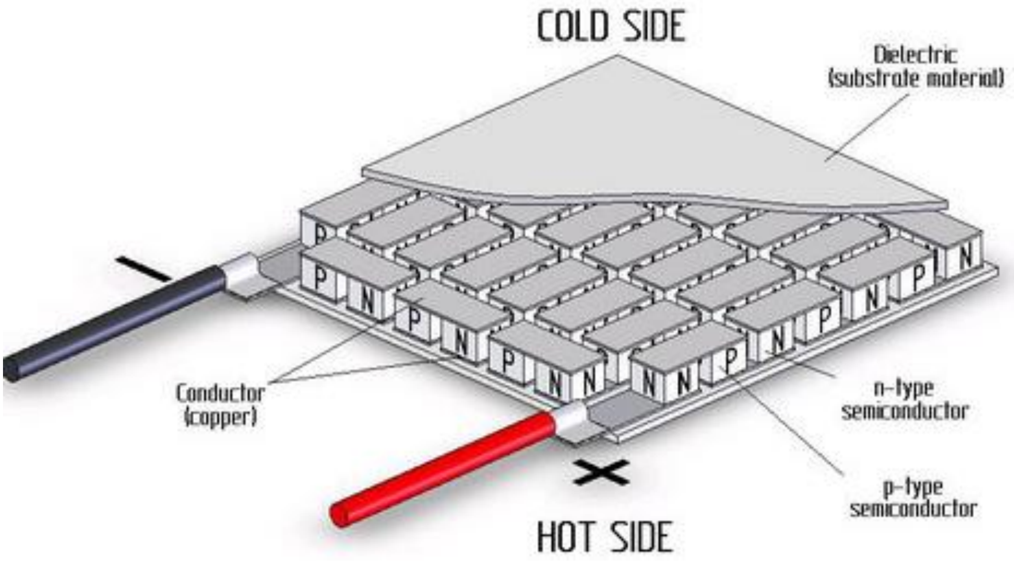

Figure 2.2: A typical thermoelectric module. (Courtesy: Google images).

2.3 Automotive ThermoElectric Generator (ATEG)

In this case, the hot side corresponds to the hot gases from the exhaust of an IC engine. Usually the cold-side is usually the circulating engine coolant liquid though it can be either the ambient air. When hot exhaust from the engine passes through an ATEG, the charge carriers of the semiconductors within the generator diffuse from the hot-side to the cold-side. The build-up of charge carriers results in a net charge, producing an electrostatic potential, while the heat transfer drives a current. With exhaust temperatures of 500°C or more, the temperature difference between exhaust gas on the hot side and coolant on the cold side is several hundred degrees. Figure 2.3 show the concept of “Thermoelectric effect” adapted to automobiles.

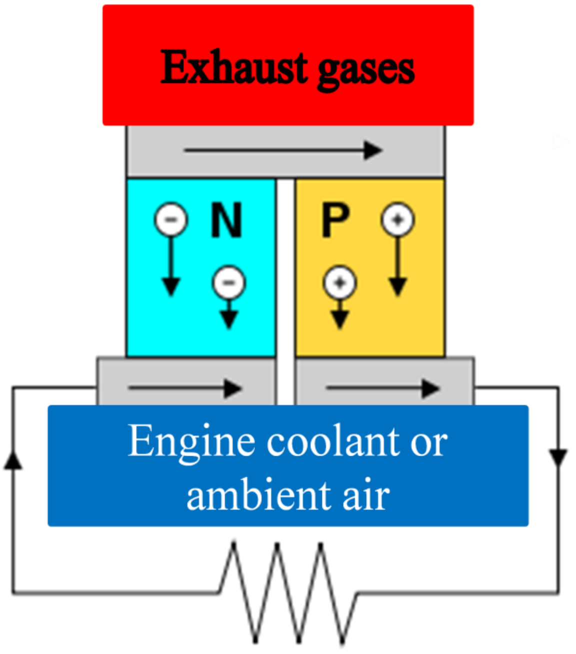

Figure 2.3: Adaption of Thermoelectric effect to automobiles.

2.4 Current Status of ATEG System

ThermoElectric devices as waste heat recovery system were present as early as 1980s in space ships. This is mainly owing to the low efficiency and high cost of these devices. But with the improvements in the material technology, TEGs power output and efficiency of conversion (thermal to electrical) has improved to a significant level so that the applications of TEGs in an automobile have become viable (technically and financially).

Currently many Automobile OEMs (Original Equipment Manufacturers), like Ford, GM and BMW etc, have been actively researching on the potential and feasibility of TEG devices in an Automobile. Some of the OEMs, like Jaguar and Volvo cars etc, have partnered with research universities (mainly USA and Europe) to develop TEG devices for Automobile applications. In India, IISc (Indian Institute of Science) have been researching on TEG devices for the past 2-3 years.

Commercially, ATEG devices are available in some of the online shopping website as experimental and hobby kits for students and researchers. But these are very highly priced, at around USD 600 for a significantly powered device. These prices are bound to come down in the next 5-6 years once TEGs for Automobile applications are researched, developed and mass produced.

CHAPTER 3: MATHEMATICAL MODEL OF ATEG

3.1 Figure of Merit – ZT

The effectiveness of a ThermoElectric material is given by a dimensionless parameter called its "figure of merit – ZT", given by equation 1.

$$ZT = \frac{\alpha^2 \sigma}{\lambda} T \tag{1}$$

Where,

α → Seebeck coefficient of TE material (V/degC)

σ → Electrical Conductivity of TE material (S/m)

λ → Thermal conductivity of TE material (W/mK)

T → Absolute Temperature of TE material (K)

The variation of ZTs v/s temperature of both p-type and n-type semiconductor thermoelectric materials are shown in Figure 3.1. By knowing the hot side (Exhaust gas) and cold side (Engine coolant liquid) temperatures, we can easily interpolate the ZT of a thermoelectric material from Figure 3.1.

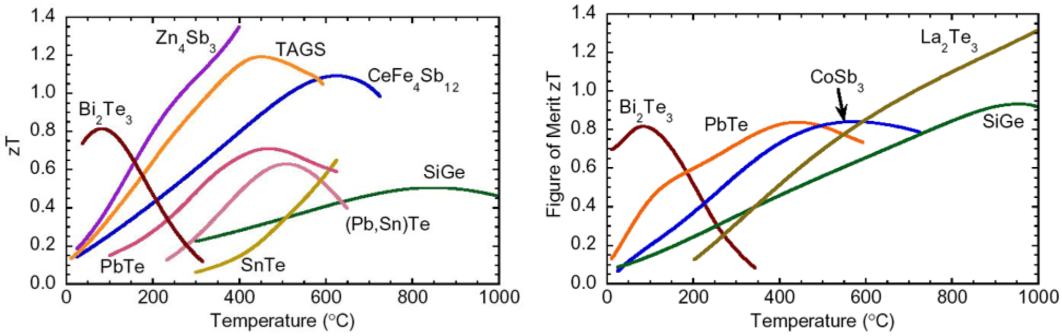

Figure 3.1: Figure of merit ZT of p-type and n-type semiconductor thermoelectric materials (Thermoelectric material ZT variation with temperature). [J. LaGrandeur, D. Crane, S. Hung, B. Mazar and A. Eder 2006].

3.2 Efficiency of Conversion

Efficiency of a thermoelectric device is directly related to the overall device ZT (combination of all the individual material's ZT), as shown in equation 2.

$$\eta_{TE} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h} \quad (2)$$

where,

T_h → Hot side Temperature (K)

T_c → Cold side temperature (K)

As ZT of the device increases, the efficiency increases and vice versa. Theoretically ZT of a material can increase to infinity, leading to device efficiency equal to the Carnot efficiency (working between the same temperature limits).

3.3 Heat Transfer and Electrical Parameters

We know that, efficiency is nothing but the input (heat transfer) over the output (electrical power). Therefore, by modeling heat transfer through the thermoelectric materials, we can get the electrical power output.

Heat transfer through the thermoelectric material is treated as a thermal resistance network with exhaust gas, exhaust pipe, ceramic layer, metal contacts (hot side), thermoelectric material, metal contacts (cold side), coolant pipe and coolant liquid treated as series elements. The equation 3 illustrates the above concept. [YUNUS A. CENGEL 2003].

$$Q = T_1 – T_2 / R_{th} \tag{3}$$

where,

$Q \rightarrow$ Rate of heat transfer (W)

$R_{th} \rightarrow$ Total thermal resistance of all the elements connected in series or parallel (K/W)

$T_1 \rightarrow$ Hot side temperature (K)

$T_2 \rightarrow$ Cold side temperature (K)

In automobile application, for which the modelling is carried out, the temperature difference obtained is upwards of 300 K. The electrical power obtained from the ATEG can again be divided into its voltage and current. The Seebeck coefficient (S) of the thermoelectric material is used to obtain the voltage across a material. This is illustrated in equation 4.

$$V = S*(T1 – T2) \tag{4}$$

where,

$V \rightarrow$ Voltage (V)

$S \rightarrow$ Seebeck coefficient (V/K)

The electrical power is divided by the voltage (estimated as in the above equation) to obtain the current through the ThermoElectric material.

3.4 Auxiliary Systems Required to Realise ATEG

In an Automobile, one needs to charge the battery and the battery in turn supplies electrical power to the load. This electrical power, to charge the battery, is supplied by the ATEG. Therefore, the voltage from the ATEG should be constant and slightly higher than the battery voltage of 12 V. This is done by a DC–DC Buck-Boost converter [David. Yan 2011] and it is mathematically modeled as shown in the below equation. A typical Buck-Boost converter circuit is shown in the Figure 3.2.

$$\frac{V_o}{V_i} = \left(\frac{-D}{1-D}\right)$$

where,

V_o → Output voltage (V)

V_i → Input voltage (V)

D → Duty cycle (0-1)

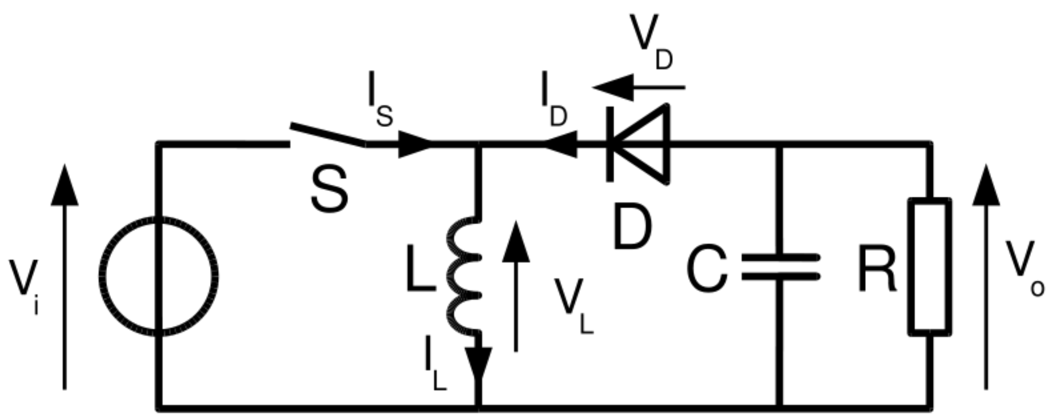

Figure 3.2: Circuit diagram of a Buck-Boost converter.

Another important system to model is the transient heat transfer from the fluids (exhaust gas or the engine coolant liquid) to the pipes. This is modeled in accordance to the transient heat conduction and convection phenomenon as shown in the below equation.

$$\begin{pmatrix}\text{Heat transfer into the body}\\ \text{during } dt\end{pmatrix} = \begin{pmatrix}\text{The increase in the}\\ \text{energy of the body}\\ \text{during } dt\end{pmatrix}$$

$$hA_s(T_\infty - T)\,dt = mC_p\,dT$$

where,

h → Convective heat transfer coefficient between fluid and pipe wall (W/m*K)

A_s → Surface area of pipe wall (m^2)

T_∞ → temperature of the fluid (K)

T → Temperature of the pipe wall (K)

C_p → Specific heat at constant pressure of pipe wall (J/Kg*K)

m → Mass of the pipe wall (Kg)

The values for the above mention pipe geometries are taken from a test car's exhaust and coolant pipe. With these mathematical equations we model the ATEG system and is described in detail in the next chapter.

CHAPTER 4: MODELING OF AN ATEG

4.1 Overview

The above said basic mathematical equations are used to model a single thermoelectric material. Many such thermoelectric materials are connected together, keeping in mind the cost constraint, space constraint (volume constraint) and the target electrical demand of the automobile, to form a thermoelectric module. ATEG system is modeled and simulated in MATLAB/Simulink environment. The model requires the exhaust gas and engine coolant liquid's temperature and mass flow rate as inputs and the geometrical dimensions of the thermoelectric material(s) and their properties as model parameters, as shown in Figure 4.1. [J. LaGrandeur et al. 2006].

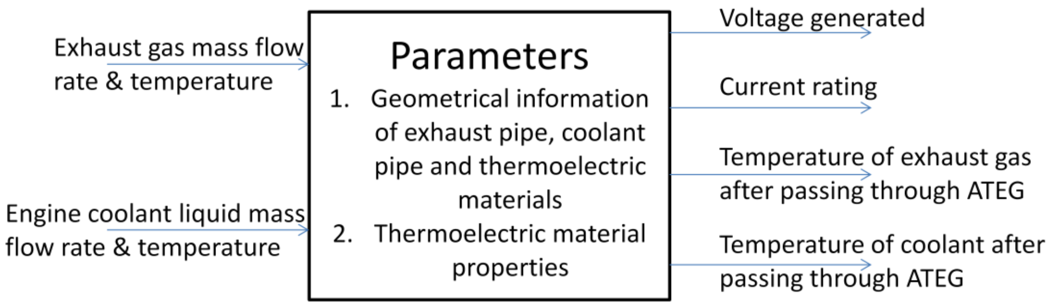

Figure 4.1: Inputs, outputs and parameters for the ATEG model developed in MATLAB/Simulink.

The inputs to this model are given from the target engine test bench data. Another important consideration is the place in the Automobile's exhaust and coolant pipe, that these inputs are taken. After due consideration of the flow characteristics of the various fluids in an IC engine, the most suitable place for installation of ATEG is decided. [John. B. Heywood 1998]. The place of installation of the target ATEG in the automobile is shown in Figure 4.2.

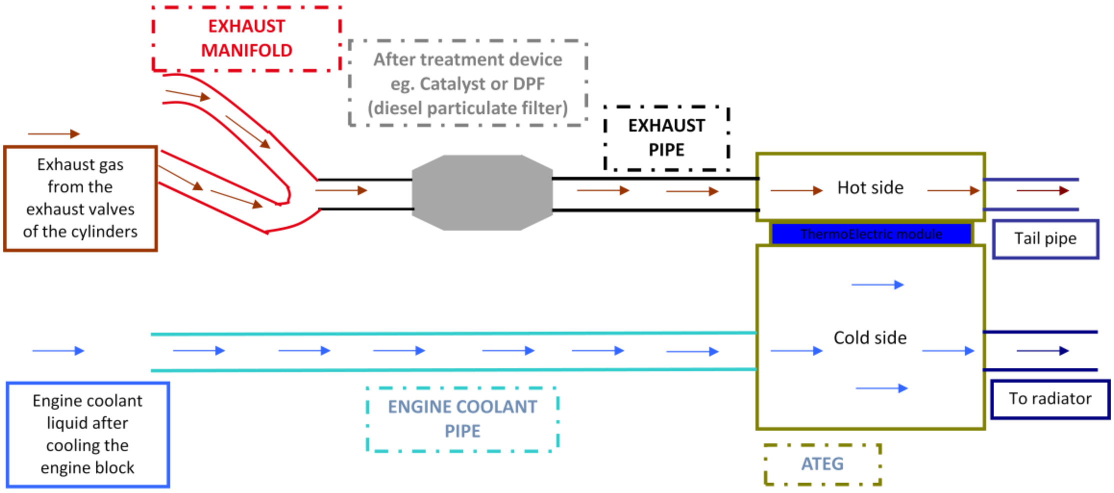

Figure 4.2: Place of installation of ATEG in an IC Engine flow path.

4.2 MODEL DEVELOPED

The model was developed in MATLAB/Simulink environment. The main aim was to accurately model the ATEG system for computer simulation. In this section some of the main sub systems which are modeled are shown, and the inputs and results are discussed in the further sections.

Figure 4.3 shows the ATEG system model developed in MATLAB/Simulink environment. There are plenty of subsystems modeled to replicate various processes in ATEG system. These are briefly discussed in the previous chapter (mathematical model of ATEG). As you can see the model requires as inputs the following –

1. Exhaust gas temperature, density and mass flow rate.
2. Engine coolant liquid's temperature and mass flow rate.

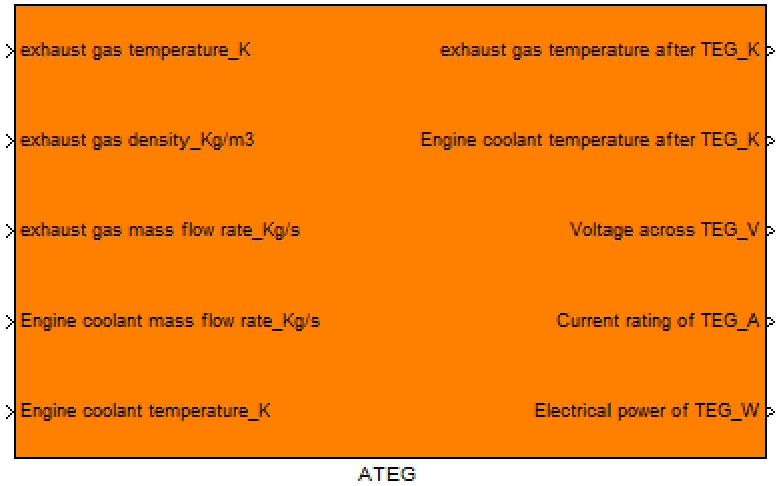

Figure 4.3: ATEG model in developed in MATLAB/Simulink.

The model gives the following as outputs –

1. Exhaust gas temperature after passing over ATEG.
2. Engine coolant liquid's temperature after passing over ATEG.
3. Voltage, Current and Electrical power of the ATEG.

Figure 4.4 shows the important sub systems involved in the ATEG system model. The light blue blocks indicate transient heat transfer from the fluid (Exhaust gas or Engine coolant liquid) to the pipe walls. The red blocks indicate the power conditioning system, which includes the DC-DC Buck Boost converter, to keep output voltage constant. The green block indicates the modeling of the TEG device.

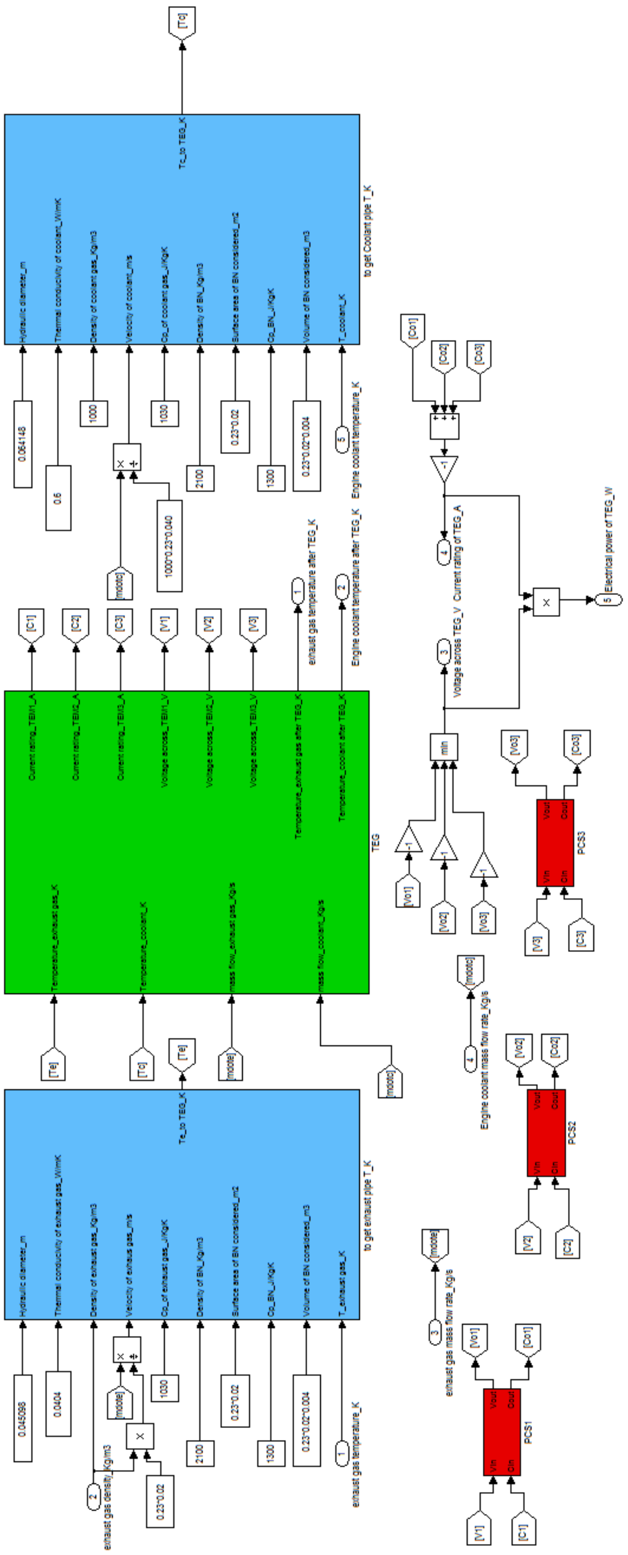

Figure 4.4: Important sub systems in the ATEG model developed.

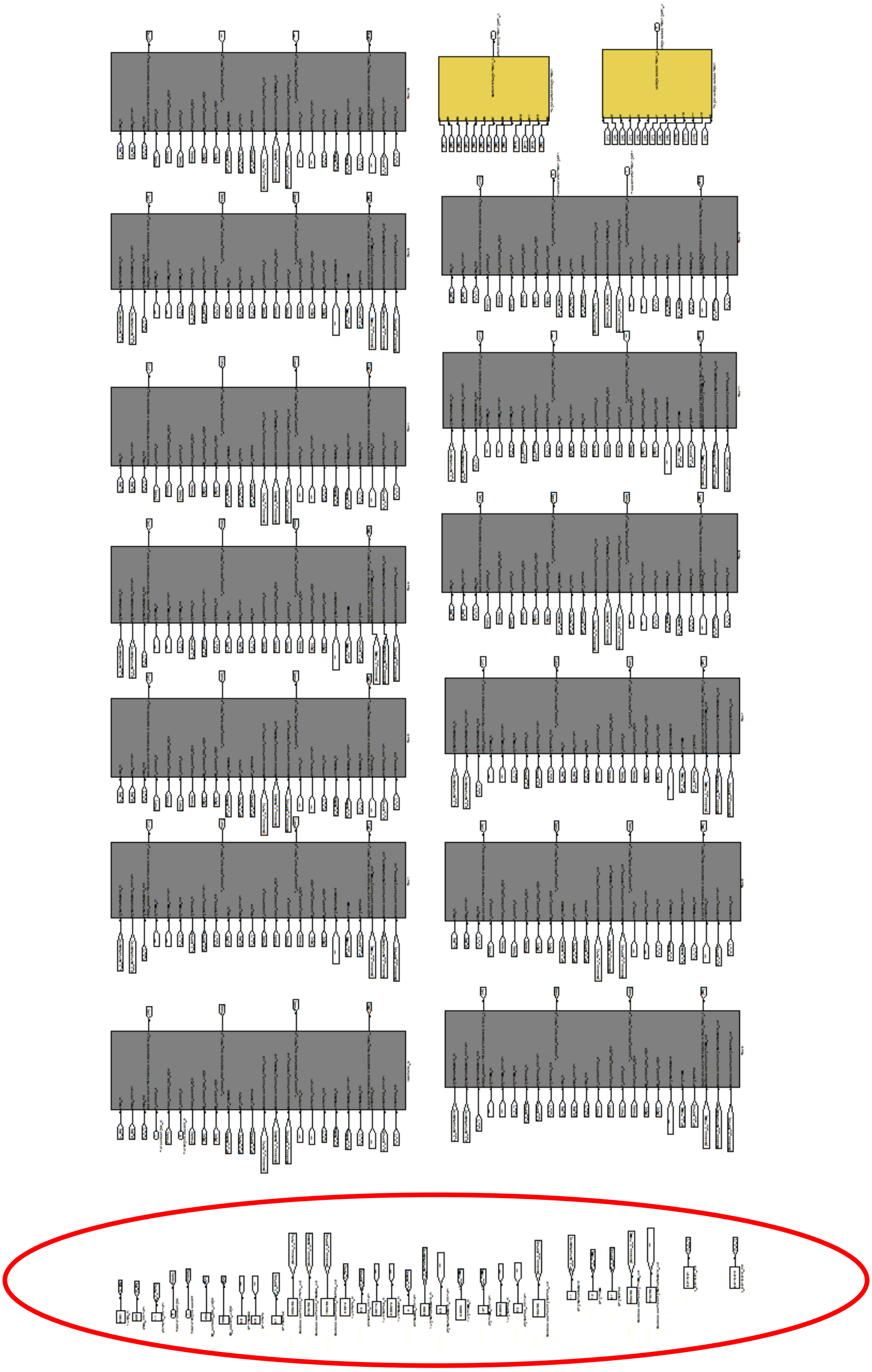

Figure 4.5: TEG device model developed.

Figure 4.5 shows a screen shot of the TEG model developed in MATLAB/Simulink. The model is developed based on the mathematical model described in Chapter 3. As highlighted in the red oval mark, the TEG model requires geometrical information and the material properties of the ThermoElectric materials that are used in the device. We call them model parameters, as we need to change them only when changing the rating of the ATEG system, and not inputs that come from the Automobile.

Figure 4.6 shows how the model, that is developed, is realized physically. The square boxes indicate the direct inputs from the Automobile. The rounded edge box indicates the model parameters. The circles indicate outputs from the ATEG system. The solid black arrows indicate heat transfer from the fluid (Exhaust gas or Engine coolant liquid) to the pipe wall. The hollow black arrows indicate the direction of heat transfer through the ATEG. Input 1 represents the exhaust gas characteristics required (temperature, density and mass flow rate). Input 2 represents the Engine coolant liquid's characteristics required (temperature and mass flow rate). Model parameter 3 represents the geometrical information and the material properties of the ThermoElectric materials used in the TEG device model. Output 1 represents the Exhaust gas temperature after passing over ATEG. Output 2 represents the Engine coolant liquid's temperature after passing over ATEG. Outputs 3, 4 and 5 represents the Voltage, Current and power of the ATEG.

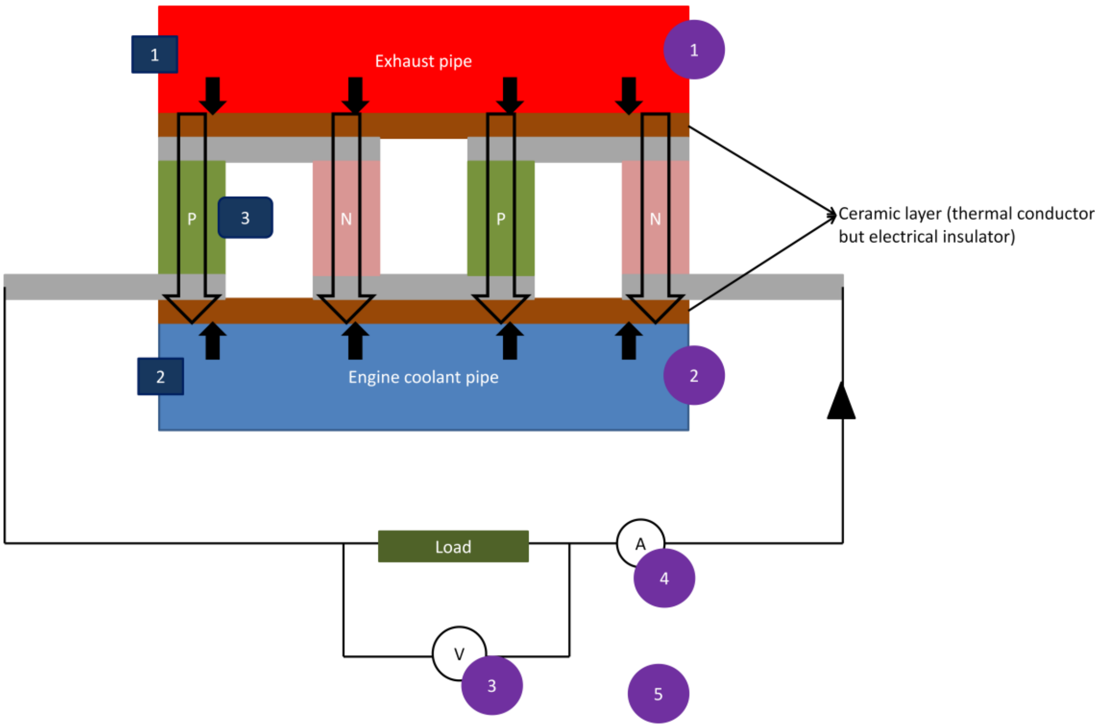

Figure 4.6: Physical realisation of ATEG model developed.

4.3 INPUTS TO THE ATEG MODEL

The inputs to the model are given from the engine test bench data. The Engine chosen is a 1.4l Diesel Engine. This Engine represents a small to mid-sized Indian Automobile. The engine is run such that the Automobile follows a particular drive cycle. A drive cycle is a series of data points representing the speed of a vehicle versus time. Drive cycle represents how a typical Automobile runs in a day to day life. A drive cycle is usually used for emission testing, fuel economy testing etc. Generally each country will have its own standard drive cycles for testing purposes (eg – Indian Drive Cycle, New European Drive Cycle etc). A typical drive is shown in Figure 4.7.

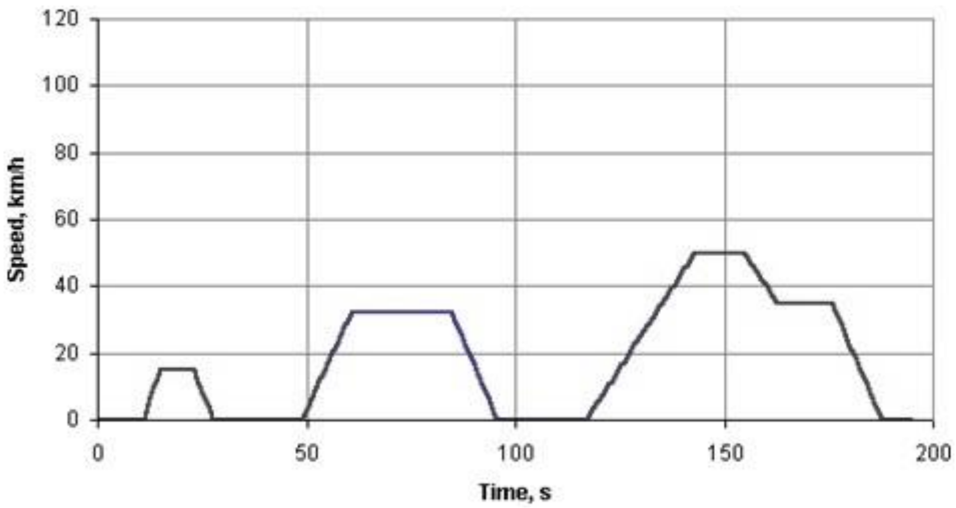

Figure 4.7: A typical drive cycle profile. (Courtesy: Google images).

The Engine is run for a drive cycle profile and the data at the required points are taken. A drive cycle lasts for 1200s and three drive cycle profiles are added together as inputs to the ATEG model, as shown in Figure 4.8.

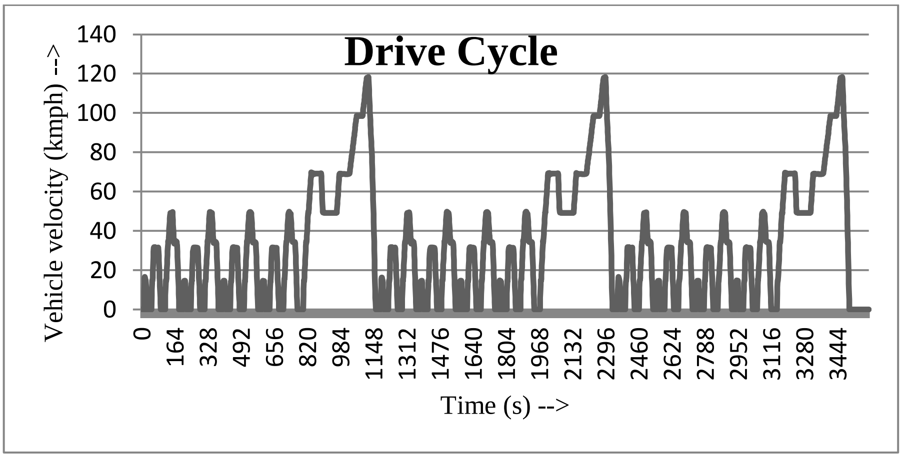

Figure 4.8: Drive cycle for which the Engine is run.

For the drive cycle profile as in Figure 4.8, the inputs of Exhaust gas temperature and mass flow rates are as shown in the Figures 4.9 and 4.10.

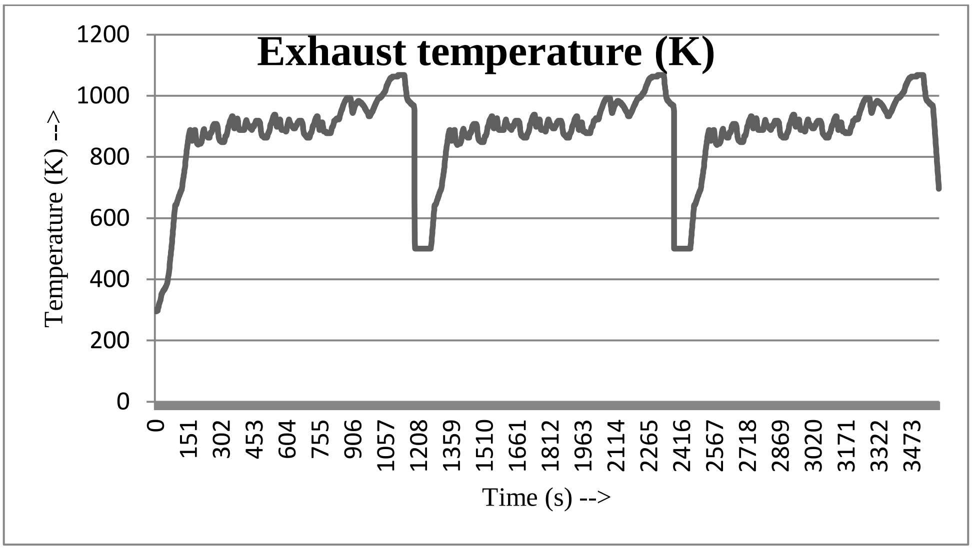

Figure 4.9: Exhaust gas temperature (K) at the point of interest vs. time (s).

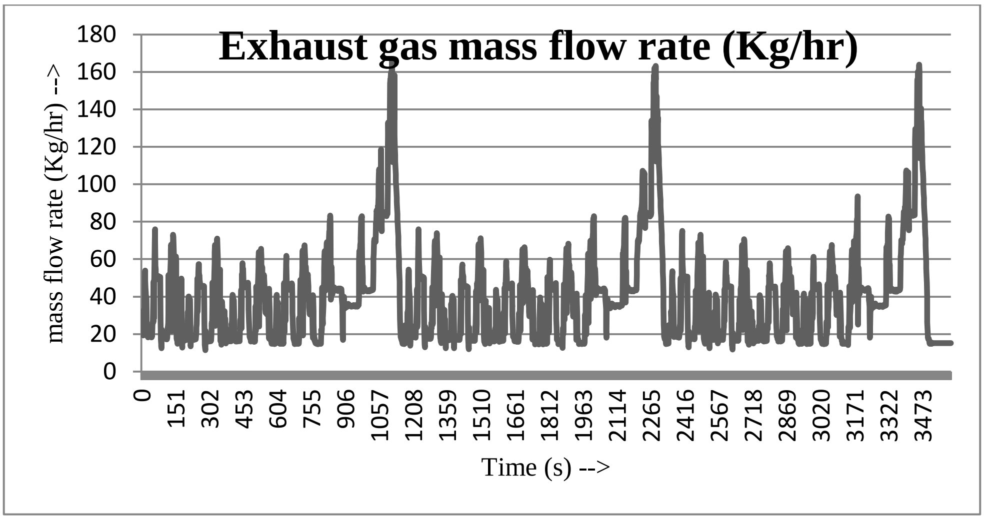

Figure 4.10: Exhaust mass flow rate (Kg/hr) at the point of interest vs. time (s).

The engine is run for a drive cycle as shown in the Figure 4.8, and the values of the variable we are interested in, are as shown Figures 4.9 and 4.10. The peaks correspond to the points where the vehicle velocity goes to 120 Kmph in the drive cycle. The immediate dip in the graphs, after the peak; only represent the adding of the next drive cycle data.

The other inputs are treated as follows –

- Exhaust gas density is treated a constant (0.65 Kg/m^3). This is the usual density of Exhaust gas though accurate density can be obtained by getting the Exhaust gas pressure and dividing it by the gas constant and Exhaust gas temperature.
- Engine coolant liquid’s temperature and mass flow rates are set at the thermostat opening values at 363 K and 18.9 Kg/min respectively.

4.4 Simulation Results

For these inputs, the results of the ATEG model are shown in Figures 4.11, 4.12, 4.13, 4.14 and 4.15.

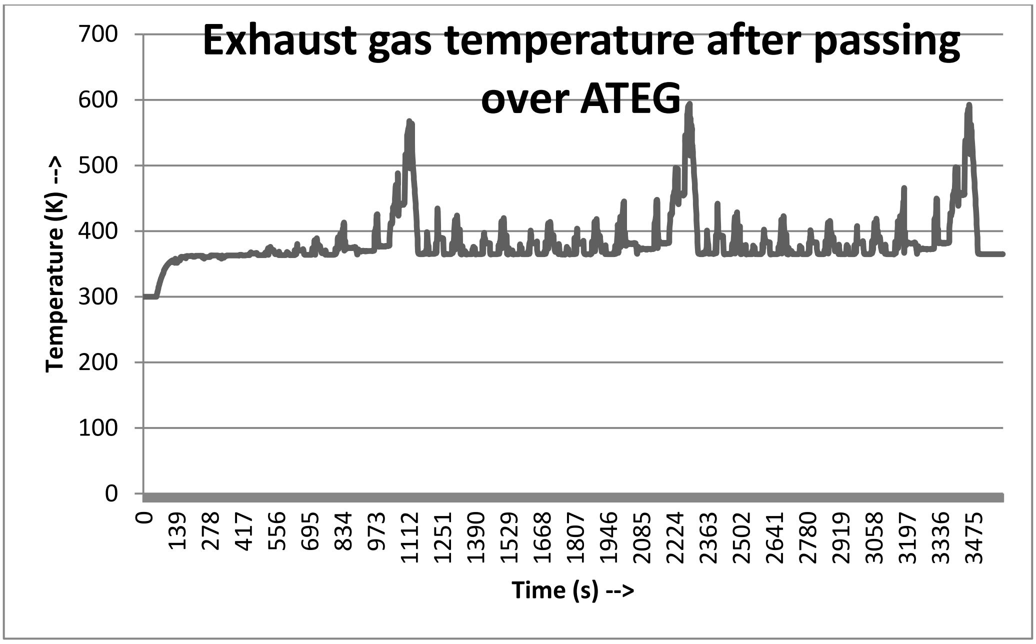

Figure 4.11: Exhaust gas temperature (K) after passing over ATEG vs. time (s).

As we can see from the Figure 4.11, the Exhaust temperature has a significant drop of about 250 K. This is because a part of the heat energy from the Exhaust gas reflects in the form of electricity generated by the thermoelectric effect.

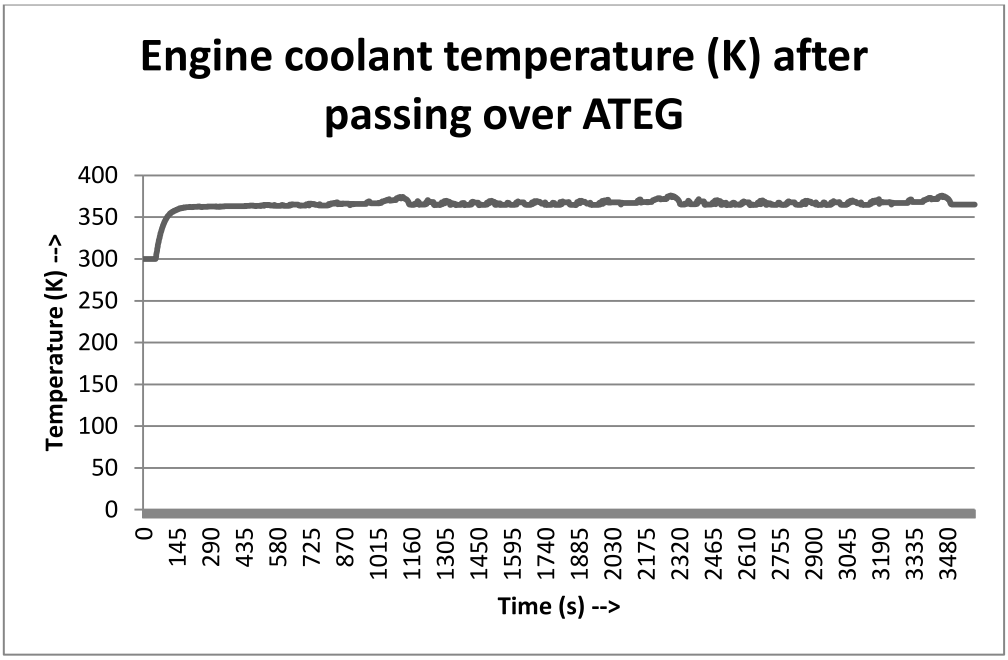

Figure 4.12: Engine coolant liquid’s temperature (K) after passing over ATEG vs. time (s).

As we can see from Figure 4.12, there is no significant rise in the Engine coolant liquid’s temperature (less than 10 K). This is because of heat transfer between a liquid to solid is more than a gas to liquid, hence heat transferred by the Exhaust gas to the Engine coolant liquid through the thermoelectric materials does not significantly rise the Engine coolant liquid’s temperature.

Figure 4.13 shows the output voltage being controlled at 14.4 V by the DC-DC Buck Boost converter. This is required in an ATEG system due to the fact that Automobile electrical loads are connected to the battery and an ATEG system is used to charge the battery. The Automobile battery is usually at 12 V and the source for charging the battery is usually at a slightly higher voltage (typically 14.4 V).

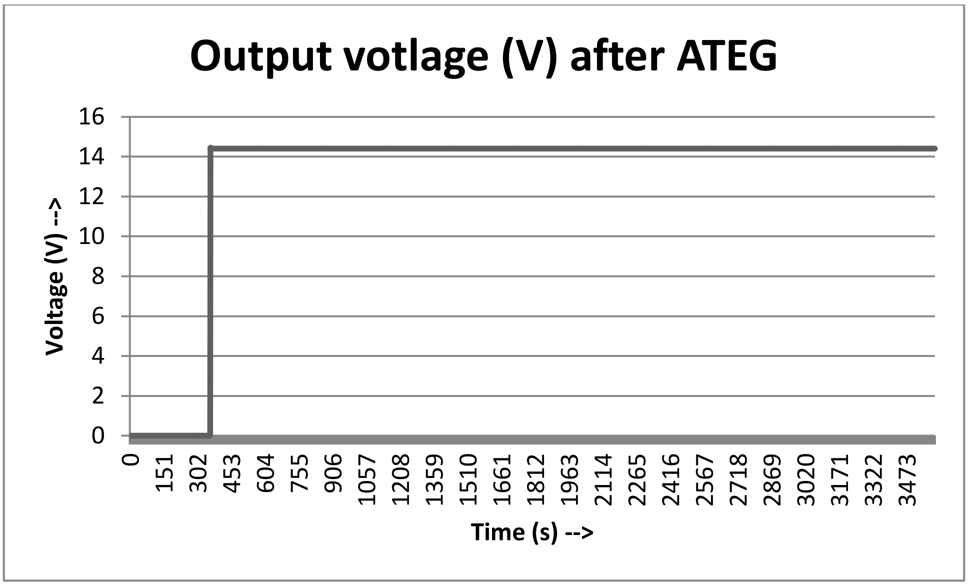

Figure 4.13: Output voltage (V) vs. Time (s).

Figure 4.14 shows the current carrying capacity of the ATEG. The current profile is similar to the alternate current in a similar sized Automobile.

Figure 4.15 shows the electrical power from the ATEG. It is obtained by multiplying the voltage and current. The peaks go beyond 1 KW and the average over the drive cycle is about 600 W.

The simulation results show that the output current and hence the electric power varies with many factors and is not a constant as the inputs are not constant. Here we observe peaks in the electric power output from the ATEG and this corresponds to the peak (i.e. 120 Kmph) in the drive cycle.

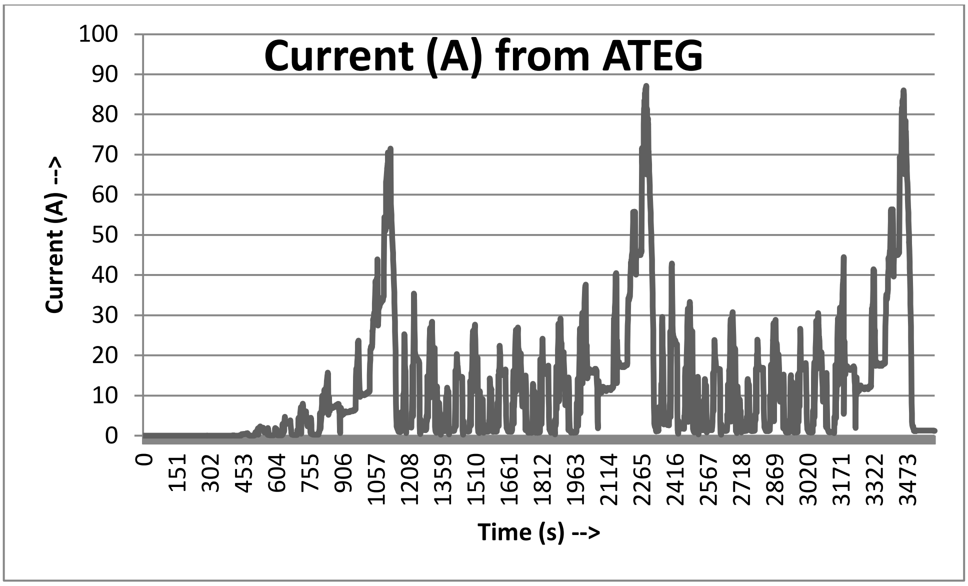

Figure 4.14: Output current (A) profile vs. Time (s).

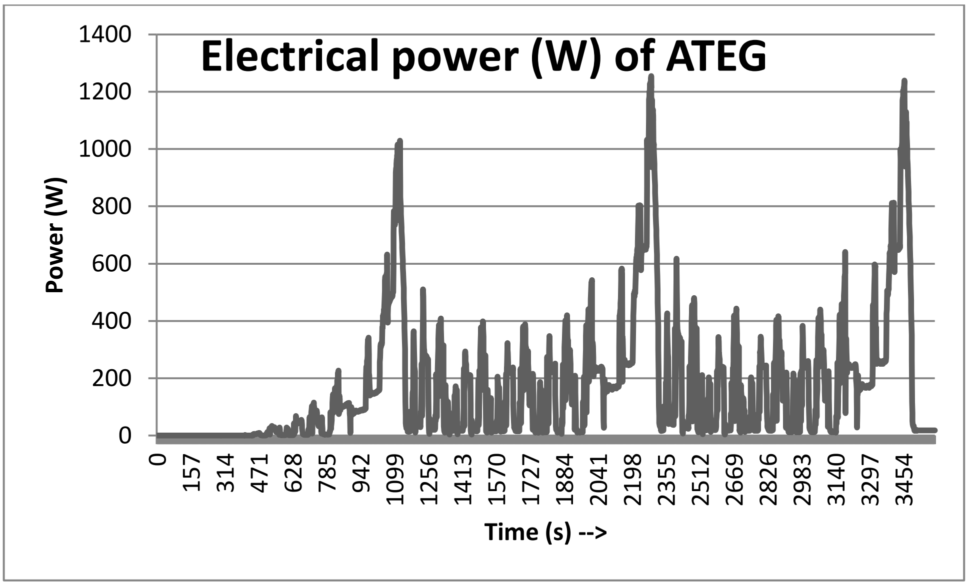

Figure 4.15: Electrical power profile of ATEG vs. Time (s).

4.5 Conclusion

The simulation results are encouraging to proceed further in developing the ATEG system for Automobiles. The Engine coolant liquid’s temperature does not increase significantly and hence we can say that increasing the Radiator’s capacity is not required. Figure 4.16 shows schematic diagram of the overview of ATEG’s addition in an Automobile. The already available Engine Control Unit (ECU) gives the required pulse duration to the DC-DC Buck Boost converter by sensing the output voltage from the TEG.

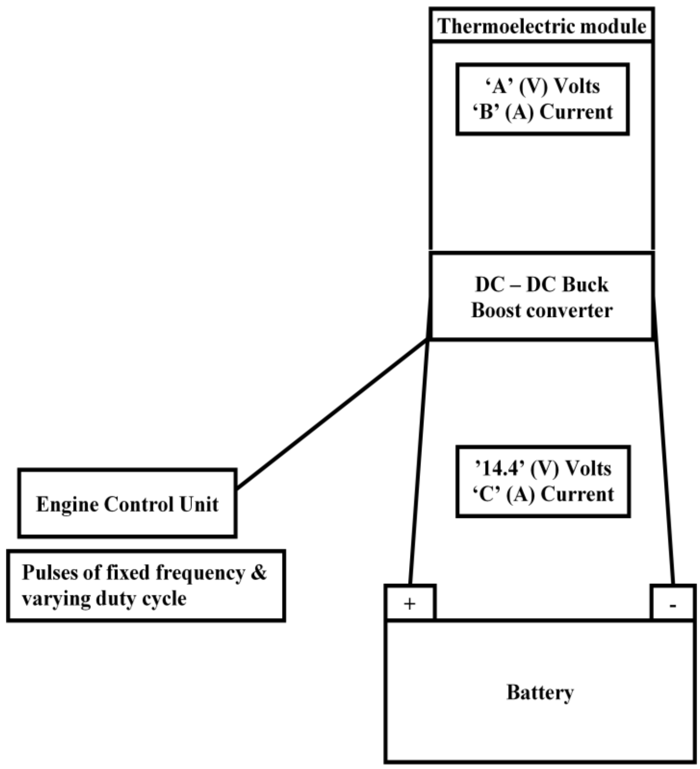

Figure 4.16: Schematic block diagram representing ATEG’s addition in an Automobile.

CHAPTER 5: CONTROL STRATEGIES

5.1 Control Logic

Thermoelectric materials and modules have been a major focus for automotive applications; however, controls will be required for the successful ATEG application. The controls consist of sensors, actuators, and control logic. The specific control components are primarily dependent on the ATEG design for a given application. This thesis will focus primarily the functions needed, not the specific sensors and actuators. [Francis Stabler 2012]. Some of the control functions needed are the following –

1. ATEG Hot side heat exchanger bypass
2. Engine coolant pump control
3. Engine coolant flow controls
4. Generator control

1. ATEG Heat exchanger by pass valve – As shown in Figure 5.1, the control valve distributes some of the exhaust gas flow to pass over the ATEG and the rest of it, to bypass it. The requirements of this control are as follows –

1. ThermoElectric materials will be damaged by the worst case exhaust temperature. Worst case temperature is a very short term event and during this time, the Exhaust gas will be bypassed by the control valve. This control valve can take the input from the temperature sensor mounted on the hot side heat exchanger.
2. Excessive exhaust backpressure will reduce the engine power output and reduce fuel efficiency. The bypass should be activated when high flow rates are expected or measured. Backpressure limit is a function of the specific engine and exhaust system with the heat exchanger as the restrictor. Rapid

throttle opening is an advance indication of high exhaust flow. A sensor could measure exhaust pressure, but more likely the bypass logic would use a calculated flow value from the engine controller

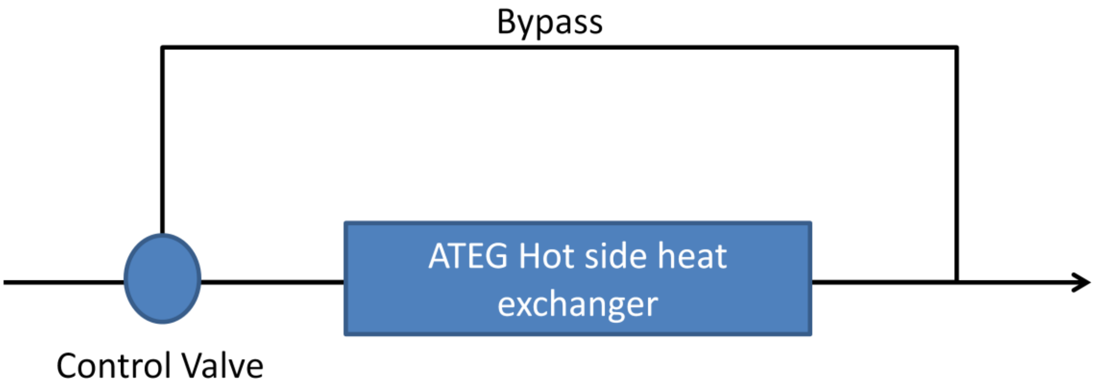

Figure 5.1: ATEG Hot side heat exchanger by pass.

2. Engine coolant pump control – As shown in the Figure 5.2, a variable speed electric pump is needed to optimize power usage and coolant flow. This control uses a temperature sensor in the output of the ATEG coolant flow as a logic input.

3. Engine coolant flow controls – As shown in the Figure 5.3, the control valve bypasses the coolant over the Radiator. This is for a very short period during Engine warm up. The ATEG heat exchanger can be used to provide warm coolant for rapid engine warm-up, for increase in fuel economy and improved passenger comfort. Logic can use the engine coolant temperature sensor as input. For this function, valves route coolant from engine to ATEG and back to engine, bypassing the radiator during the warm-up period

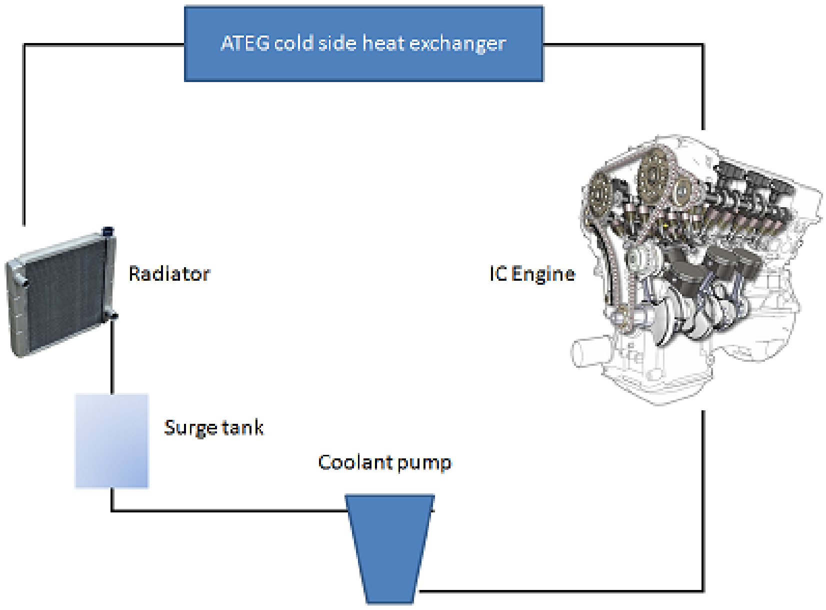

Figure 5.2: Engine coolant pumps control.

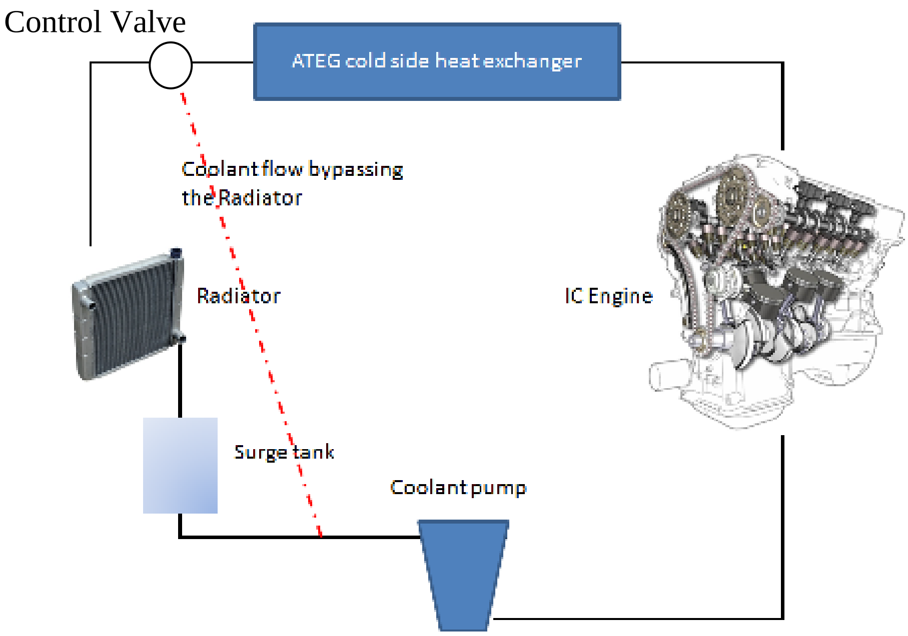

Figure 5.3: Engine coolant flow controls.

4. Generator control – Needed to optimize the fuel economy provided by the ATEG when the electrical loads are light. When the electrical power demand (load) in the Automobile is low and when the battery is charged beyond a threshold, we require a less than average ATEG output. When the ambient temperature allows easy charging of the battery (neither too high nor too low for specific battery chemistry), keep the generator off until the ATEG output is functioning or additional power is required. Over-ride if the battery state of charge is below a set value. This control logic takes the inputs from battery state of charge sensor and the electrical load sensor.

5.2 Choice for Controller

The control logic in an Automobile for an ATEG can take any of the three below mentioned choices

1. Stand-alone electronic control unit.

  → Easier to implement, very desirable if optional

  → Serial data interface with engine controller

2. Integrated into the Engine Control Unit (ECU).

  → Less expensive if standard equipment

  → Easier to use engine sensors and data

3. Integrated into the generator controls.

  → Provides a single power control

  → Very unlikely choice

5.3 Conclusion about Control Strategies

Controls form a very important part of any system that is being introduced to the already vast and established automotive system. The main objectives of these controls are to optimise fuel efficiency in an automobile. The functionality of ATEG with controls can be summarized in the following points.

- ➔ ThermoElectric modules remain the most important part of ATEG design.
- ➔ ATEG application will not take place unless a good control system is developed.
- ➔ The control system can make the difference between a barely functional ATEG and an efficient, cost effective ATEG.

CHAPTER 6: CONCLUSION

This thesis work looks at the potential of an ATEG system in an Automotive system. The approach taken in this project/thesis work is to accurately model an ATEG system for computer simulation. This significantly reduces the cost involved in designing the system in laboratory environment. We can infer the following from the project/thesis work.

1. The temperature of the Engine coolant liquid does not rise significantly. Hence, we can say that, Radiator redesign is not required.
2. ATEG system, in the simulation level, gives electrical power comparable to a alternator in a similar sized Automobile. Hence ATEG system can replace fossil fuel based electricity generated by the Alternator in the existing Automobiles.
3. ATEG system can also be used for treating exhaust gases (active after treatment devices).
4. In the current Automobiles, the Alternator is directly connected to the crankshaft of the Engine, via a belt, and hence replacing the Alternator will reduce load on Engine. This reduction in load on the Engine will increase fuel efficiency of the Automobile and also reduce its’ emissions.
5. All these will reduce the carbon foot-print of Automobiles, give a greener image to Automobiles and increase its’ saleability for the Automobile OEMs.
6. ATEG technology needs a Heat source only and does not so much depend on the composition of this Heat source. Hence ATEG technology is relevant to Gasoline/petrol, diesel or Bio fuel driven IC Engines.

Figure 6.1 shows the power flow, in an Automobile, conventionally and also in the proposed ATEG system.

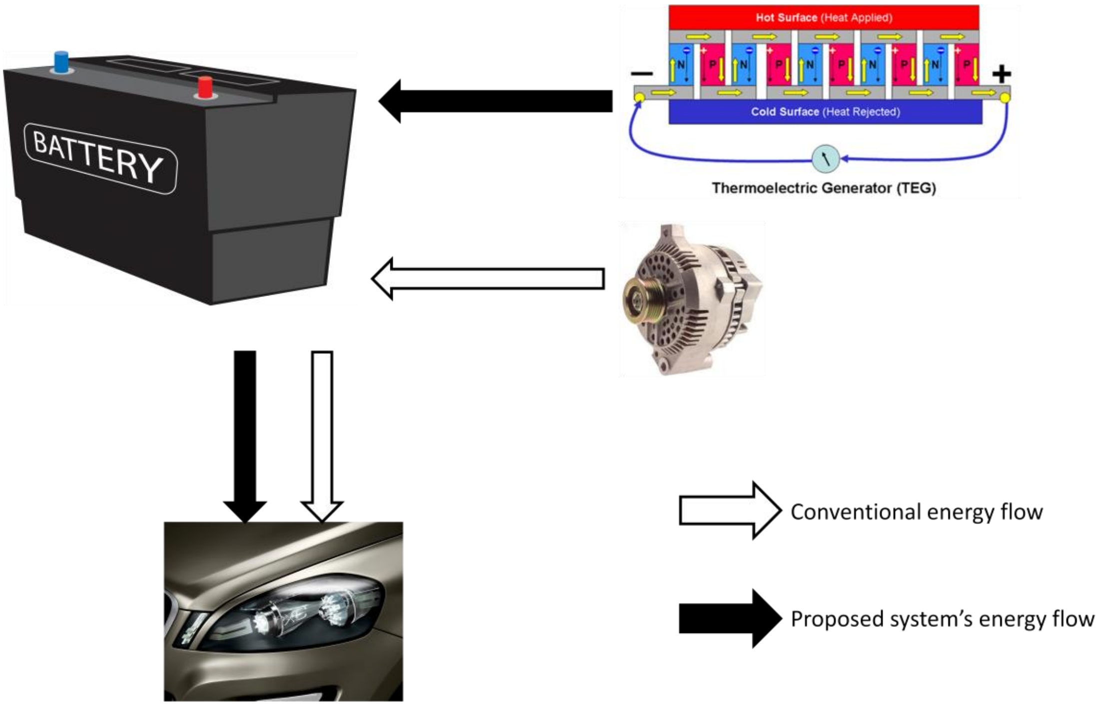

Figure 6.1: Electrical energy flow comparison between existing and the proposed system.

The next step to this work is to build a physical prototype according to the design proposed in the model and this would be discussed in detail in the next chapter.

CHAPTER 7: FUTURE WORK

The obvious next step to this project/thesis work is to build a physical prototype according to the design in the simulation model. Then to give the same inputs, as that given to the simulation model, and validate it with the simulation model developed. This project/thesis work was carried out at Robert Bosch Engineering and Business Solution Limited (RBEI), Bangalore, India as a proof of concept and after encouraging results in the simulation level, procuring (next stage) a physical prototype is initiated at RBEI and further development in the field of ATEG will be carried out at RBEI.

Figure 7.1 gives an overview on how the project/thesis is carried out and how it can be extended for future work. Detailed fluid flow in an IC Engine driven Automobile, is studied and the place of installation is decided as shown in the top part of the Figure 7.1. The point of interest in the Exhaust and the Engine coolant pipes' are indentified and these points are observed in the Engine test bench for a Drive cycle profile. Further we need to build a physical prototype in accordance with the design in the simulation and validate the physical prototype with giving the same inputs as that given to the simulation model. Further, we need to decide upon and implement controls to our ATEG for successful realization of the same.

In general ATEGs have great business potential for Automobile OEMs and Automobile related organisations in general. With the ever increasing rise of fossil fuels, environmental impact of Automobiles and relatively low efficiency of IC Engines (compared to say Turbines), ATEGs development will become a key factor in any Automobile related organisation.

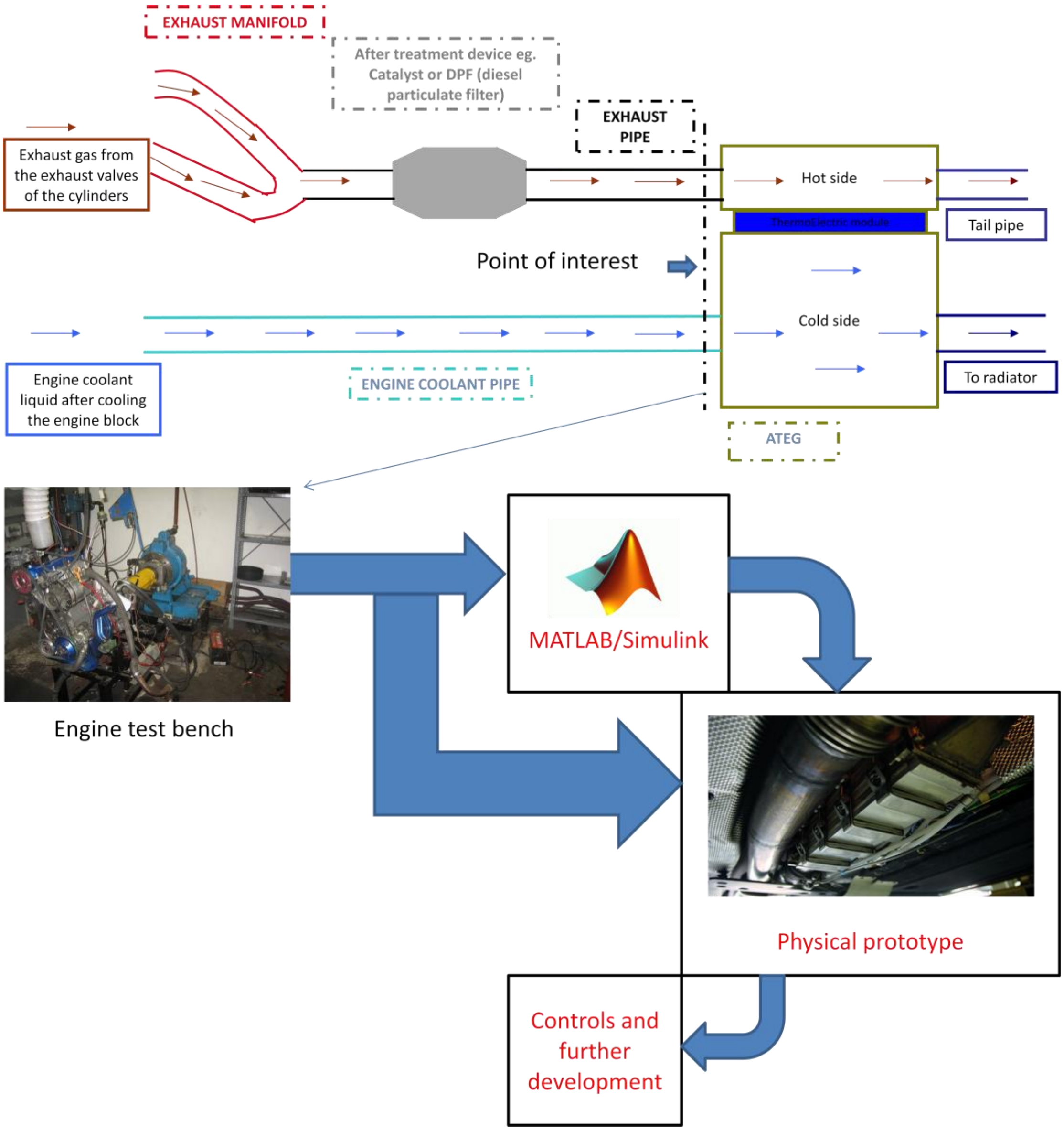

Figure 7.1: Project overview and future work.

Appendix I – Certificate of publication in the "International Journal of Science and Research (IJSR)"


IJSR

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Certificate of Publication

This is to certify that the Paper ID: IJSRON2013977, entitled

Modeling of an Automotive ThermoElectric Generator (ATEG)

Authored / Co Authored

by

Chethan R Reddy, Shrikantha S Rao, Vijay Desai, Karthikeyan Ramachandran

has been published in Volume 2 Issue 5, May 2013

in

International Journal of Science and Research (IJSR)

The mentioned paper is measured upto the required standard.

Editor In Chief

Editor In Chief

International Journal of Science and Research, India

This Certificate is Digitally Signed by Editor In Chief

Appendix II – Certificate of Internship at RBEI

Robert Bosch Engineering and Business Solutions Limited
(Formerly Robert Bosch India Limited)

BOSCH

LETTER OF REFERENCE

Date: 31.05.2013

This is to certify that Mr. Chethan R Reddy pursuing M.Tech from NITK, Surathkal, has carried out a project internship under the title "**Development of Automotive Thermoelectric Generator"** in EES department under the guidance of Mr. Karthikeyan Ramachandran (RBEI/EES4) from 04.06.2012 to 29.03.2013.

We thank him for his efforts and contribution. We wish him continued success in his future endeavors.

Robert Bosch Engineering and Business Solutions Limited

S. Anuradha Preeth

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References

Andrew P. Freedman (2011). “A Thermoelectric Generation Subsystem Model for Heat Recovery Simulations.” Master of Science thesis, Department of Mechanical Engineering, Rochester Institute of Technology, Rochester, New York 14623.

Chethan. R. Reddy, Shrikantha. S. Rao, Vijay. Desai, Karthikeyan. Ramachandran (2013). “Modeling of an Automotive ThermoElectric Generator (ATEG).” *Volume 2 Issue 5, May 2013, International Journal of Science and Research (IJSR).*

David. Yan (2011), “Modeling and Application of a Thermoelectric Generator.” Masters of Applied Science thesis, Graduate Department of Electrical and Computer Engineering, University of Toronto.

Francis Stabler (2010). “Automotive Thermoelectric Generator Design Issues.” Future Tech LLC, *DOE Thermoelectric Applications Workshop*, San Diego, CA.

Francis Stabler (2012). “Automotive Thermoelectric Generator (TEG) Controls.” *March 2012 DOE Thermoelectric Workshop*, Baltimore, MD, USA.

G. Jeffrey Snyder (2008). “Small Thermoelectric Generators.” http://www.electrochem.org/dl/interface/fal/fal08/fal08_p54-56.pdf (02 Dec 2012).

Gaowei Liang, Jiemin Zhou, Xuezhang Huang (2011). “Analytical model of parallel thermoelectric generator.” *Applied Energy – Volume 88, Issue 12*, December 2011, Pages 5193–5199.

Gregory P. Meisner (2011). “Advanced Thermoelectric Materials and Generator Technology for Automotive Waste Heat at GM.” *2011 Thermoelectrics Applications Workshop*, January 3-6, 2011, Hotel Del Coronado, San Diego, CA, USA.

Ibrahim Atassi, Ernst Bauer, Johann Nicolics, Bernhard Dange, Lukas Spendlhofer, Dennis Knospe, Florian Faistauer (2012). “Current Thermoelectric Materials and an Evaluation of Thermoelectric Material Contacting Approaches.” *Electronics Technology (ISSE), 2012 35th International Spring Seminar on*, Publication Year: 2012, Page(s): 70 - 75.

J. LaGrandeur, D. Crane, S. Hung, B. Mazar and A. Eder (2006). “Automotive Waste Heat Conversion to Electric Power using Skutterudite, TAGS, PbTe and BiTe.” *Thermoelectrics, 2006. ICT '06. 25th International Conference on*, Date 6-10 Aug. 2006.

JIHUI YANG and FRANCIS R. STABLER (2009). “Automotive Applications of Thermoelectric Materials.” *Journal of ELECTRONIC MATERIALS, Vol. 38, No. 7, 2009.*

John. B. Heywood (1998).“Internal Combustion Engine Fundamentals” *Mcgraw-Hill*, page nos. -748-816.

John LaGrandeur (2009). “Automotive Waste Heat Conversion to Power Program.” *2009 Hydrogen Program and Vehicle Technologies Program Annual Merit Review*- May 22, 2009.

John W Fairbanks (2012). “Automotive Thermoelectric Generators and HVAC.” *2012 Annual Merit Review, DOE Vehicle Technologies Program and Hydrogen and Fuel Cells Program*, Washington DC, May 14 - 18, 2012.

Kylan Wynn Engelke (2010). “NOVEL THERMOELECTRIC GENERATOR FOR STATIONARY POWER WASTE HEAT RECOVERY.” Master of Science thesis, Department of Mechanical Engineering, MONTANA STATE UNIVERSITY Bozeman, Montana.

M. Kober, C. Häfele, H. Friedrich (2012). "Methodical Concept Development of Automotive Thermoelectric Generators (TEG)." *3rd International Conference "Thermoelectrics goes Automotive"*, 23.11.2012.

Xiaodong Zhang, C.C. Chan, and Wenlong Li (2011). "An Automotive Thermoelectric Energy System with Parallel Configuration for Engine Waste Heat Recovery." *Electrical Machines and Systems (ICEMS), 2011 International Conference on*, Date 20-23 Aug. 2011.

YUNUS A. CENGEL (2003)."HEAT TRANSFER – A Practical Approach." *McGraw-Hill, 2nd edition*, page nos 209-314.

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