An Experimental Study of the Ability to Recover Waste Heat from an Old Automotive Engine Exhaust

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Abstract

Around 30-40% of the heat supplied in an internal combustion engine is rejected through the exhaust gases. So, the engine overall efficiency can be improved if this waste heat was converted to usable energy. Thermoelectric generators are solid states devices which can be used to convert thermal energy to electrical energy depending on the See beck effect principles.

In the present work; Sahin 131 H1 016; which is an old car model, was tested for thermoelectric generators device. The temperature distribution along the exhaust pipe was measured at different car speeds (0; 40; 60 and 80 km/h) with two loads. Also, the temperature distributions were measured with and without exhaust pipe insulation. The exhaust gases were analyzed to point out the car engine performance. Exhaust pipe temperature distribution can be utilized to estimate the power gain by thermoelectric generators.

Keywords: *TEG, Waste Heat, Old Car, Exhaust Gases.*

1- Introduction

Approximately 90% of the world's electricity is generated by heat energy, typically operating at 30–40% efficiency, losing roughly 15 terawatts of power in the form of heat to the environment. Thermoelectric devices could convert some of this waste heat into useful electricity [1]. Internal combustion engines capture 20–25% of the energy released during fuel combustion [2]. Increasing the conversion rate can increase mileage and provide more electricity for on-board controls and creatures comfort (stability controls, telemetric, navigation systems, electronic braking, etc.)[3].

It may be possible to shift energy drawn from the engine (in certain cases) to the electrical load in the car, e.g. electrical power steering or electrical coolant pump operation. [2]

Unlike traditional dynamic heat engines, thermoelectric generators contain no moving parts and are completely silent. Compared to large, traditional heat engines, thermoelectric generators have lower efficiency. But, for small applications, thermoelectric generators can become competitive because they are simple, compact, and inexpensive. Thermoelectric systems can be easily designed to operate with small heat sources and small temperature differences. Such small generators could be mass produced to be used in automotive waste heat recovery or home co-generation of heat and electricity.

At about 1995 the U.S. Department of Energy (USDOE) initiated a project with Hi-Z technologies to develop a thermoelectric generator (TEG) demonstrator to convert the waste heat from a heavy-duty Class 7-8 diesel engine directly to electricity. This unit used Bismuth Telluride cells and provided a nominal 1 kW. This TEG was integrated with the muffler and was installed in a heavy-duty truck. Radiator cooling water (~110˚C) was used to extract the heat from the cold side of the TEG.

The TEG was run for about 550,000 miles on the Paccar test tract. These data coupled with a first approximation analysis justified initiation of a competitive procurement to develop Thermoelectric Generators (TEG's) for transportation vehicles, to either augment or replace the alternator. The objective of these projects was to provide a 10 percent improvement in fuel economy [4]. This is the same aim for the engine waste heat recovery projects which develop bottoming cycles and electric turbo compounding, and involve adding a motor/alternator to the turbocharger shaft.

The TE modules used in a typical TEG can be classified according to the semiconductor material used and the shape, size and configuration of their thermoelectric pairs. The semiconductor material used in the fabrication of the pellets is selected according to the position of the TEG in the exhaust pipe:-

- Just behind the exhaust manifold where the temperature range of the exhaust gases is between 1000ºC and 750ºC. The thermo elements are fabricated on the basis of β-$FeSi_2$, with co-doping for n-type and adopting for p-type in [5], while in [6] the pellets were based on Si-Ge alloys.

-Between the exhaust manifold and the catalyst converter where the temperature range of the exhaust gases is between 750ºC and 400 ºC. The model proposed in [7] uses lead telluride thermo elements, type 2P and type 3N/4N. The Nissan Research Centre used PbTealloys in [8] and the same was also used by Takanose [9].

- Just behind the catalyst converter, the temperature range of the exhaust gases is between 400ºC and 200ºC. All the TEGs designed to be mounted in this position are based on bismuth telluride alloys.

Most of the new cares have TEGs installed. TEGs were installed in a BMW X6 and Lincoln MKT with at least 450w of power output achieved in road tests for both.

2- Experimental Model

2.1 Car Model

Our model is Sahin 131 H1 016; Fig. (1), which is an old car with specifications listed in Table (1).

Table (1): Sahin car specifications

Model	131 H1 016
Code	159.A2.000
Diameter × Stroke	80.5 mm ×67.4 mm
Capacity	1372 (cm^3)
Compression Ratio	1:8.3
Maximum Power	78/5500 (hp/rpm)
Maximum Torque	104/3500 (N.m/rpm)
Alternator	55 A (9 Diodes)
Temperature of Opening Refrigeration Cycle (Thermostat)	92° C ± 2
Temperature of Closing Refrigeration Cycle (Thermostat)	87° C ± 2

Fig. (1) Photo of Sahin car.

2.2 Exhaust Pipe

The exhaust pipe dimensions for the car model is shown in figure (2). Figure (3) shows the exhaust system components.

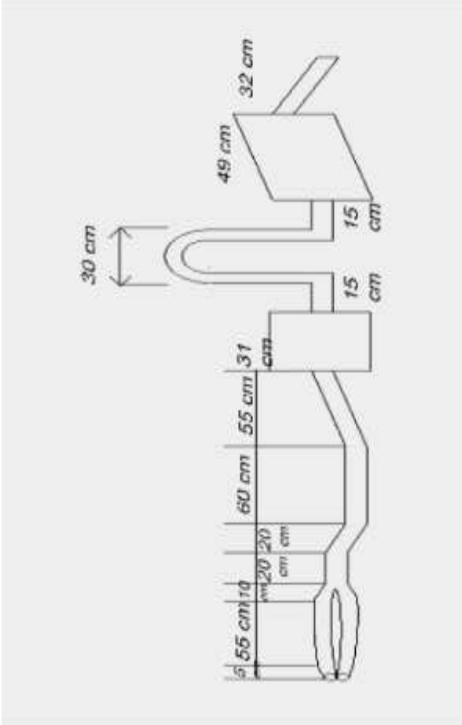

Fig. (2) Sahin model exhaust pipe.

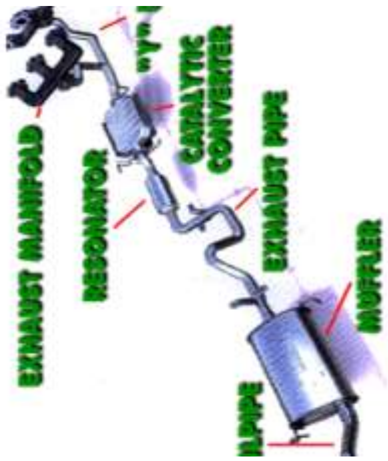

Fig. (3)Exhaust System Components.[10]

3. Measurements

3.1. Exhaust Gases Temperature

The exhaust of a four-stroke cycle engine is a two-step process: blow down and exhaust stroke. Blow down occurs when the exhaust valve opens late in the expansion stroke and the remaining high pressure in the cylinder forces the exhaust gases through the open valve into the exhaust manifold. Because of the large pressure differential across the valve, sonic velocity occurs and the flow is choked.

As the exhaust gas experiences blow down, the temperature decreases due to expansion cooling. The high kinetic energy of the gas during blow down is dissipated quickly in the exhaust manifold, and there is a momentary rise in the temperature again from the resulting increase in specific enthalpy.

The exhaust valve should open soon enough so that blow down is complete when the piston reaches BDC. At this point, the cylinder is still filled with exhaust gas at about atmospheric pressure, and most of this is now expelled during the exhaust stroke. Temperature of the gases in exhaust system of a typical SI engine will average 400°C to 600°C. This drops to about 300°C to 400°Cat idle condition and increases to about 900°C at maximum power. The average temperature in the exhaust system of a typical CI engine will be200-500°C. This is lower than SI engine exhaust because of the larger expansion cooling that occurs due to the higher compression ratios of CI engines. Exhaust temperature of an engine will increase with increasing engine speed or load, with spark retardation, and/or with an increase in equivalence ratio.

Thermocouples are widely used for temperature measurement and control. A thermocouple circuit is formed when two dissimilar metals are joined at both ends. There is temperature difference between the two ends. This difference in temperature creates a small current. This is called the See beck effect [11]. Thermocouple Type K; which has a wide range, is more proper for temperature measurement in our investigation.

Type K (chromel{90 percent nickel and 10 percent chromium}–alumel)(Alumel consists of 95% nickel, 2% manganese, 2% aluminum and 1% silicon) is the most common general purpose thermocouple with a sensitivity of approximately 41 µV/°C, chromel is positive relative to alumel. A wide variety of probes are available to cover the wide temperature range [−200 °C to +1350 °C / -328 °F to +2462 °F]. It was specified at a time when metallurgy was less advanced than it is today, and consequently characteristics may vary considerably between samples [12].

Fig. (4) Thermocouple with display unit.

The exhaust gases temperatures were measured using thermocouple sensors at seven locations on the exhaust pipe with and without pipe insulation. The first point just behind the engine outlet and the last point near the exit to atmosphere. Figures 5 and 6 are photos of exhaust pipe without and with insulation. Measurements were conducted for two different loads (120 and 365 Kg) at different car speeds (0; 40; 60 and 80 Km/h)

Fig. (5) Exhaust pipe without insulation.

Fig. (6) Exhaust pipe with Insulation.

3.2 Exhaust Gasses Analysis

Exhaust gases analysis will help to identify the following car engine problems [13]:
1- Problems of nutrient (Carburetor) or injection system,
2- Mechanical problems of the engine,
3- Leakage of dislocations,
4- Problems with the ignition system,
5- Problems of ventilation system tray attached the Positive Crankcase Ventilation (PCV),
6- Clogged filter (air filter),
7- Air injection system malfunction.
8- Problems in the evaporation control system,
9- Problems of the control system by computer,

Automotive gas analyzer (IMR® 2800-automotive emission gas analyzer) was used to analyze the car model exhaust gases. Figure(6) illustrates the IMR® 2800 Backlit LCD & Keypad.

Fig. (7)Photograph of IMR® 2800 Backlit LCD &Keypad [14].

4. Results and Discussion

Figures (8to 15) show the temperature distributions along the Shahin exhaust pipe. As may be expected, higher temperature range may be observed with insulated exhaust pipe. Also, it may be seen that the exhaust temperature in general increases with increasing car speed and/or load.

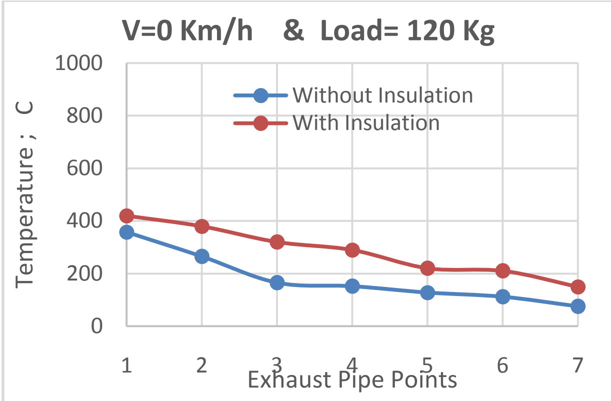

Fig. (8) Temperature distribution at zero car speed and load of 120 Kg.

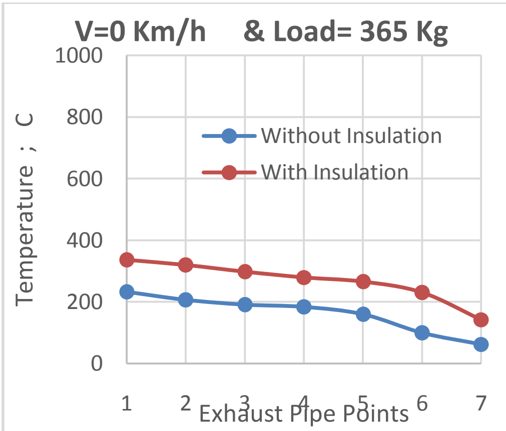

Fig. (9) Temperature distribution at zero car speed and load of 365 Kg.

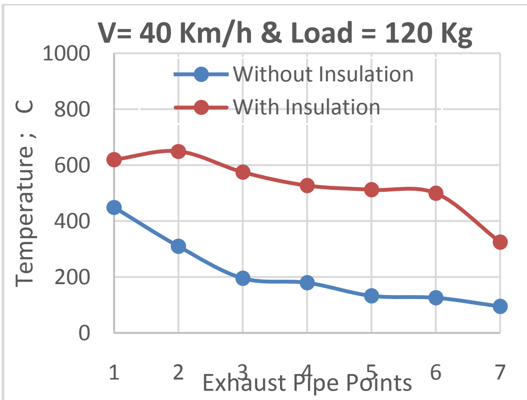

Fig. (10) Temperature distribution at 40 Km/h car speed and load of 120 Kg.

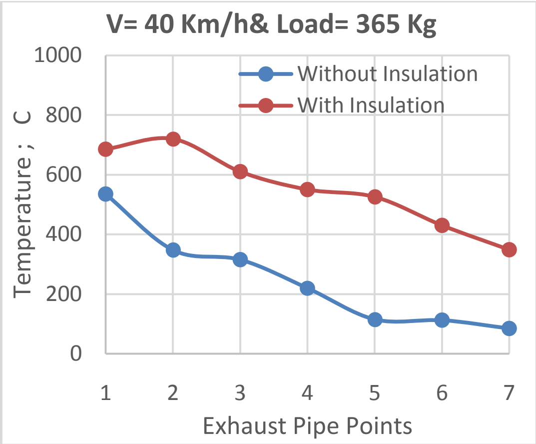

Fig. (11) Temperature distribution at 40 Km/h car speed and load of 365 Kg

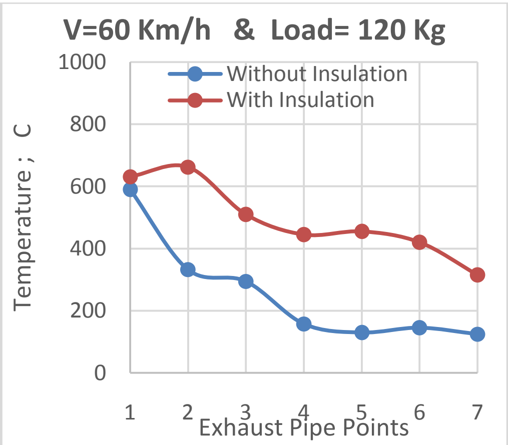

Fig. (12) Temperature distribution at 60 Km/hcar speed and load of 120 Kg.

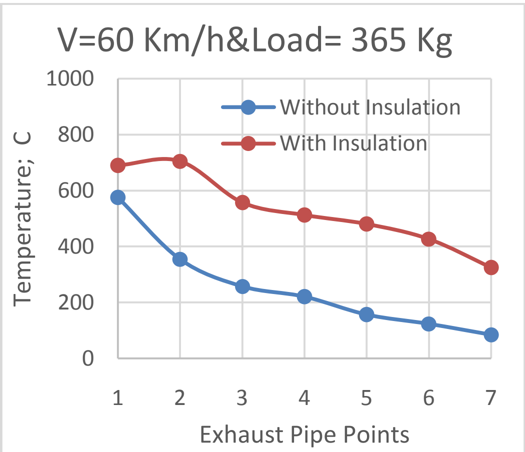

Fig. (13) Temperature distribution at 60 Km/hcar speed and load of 365 Kg.

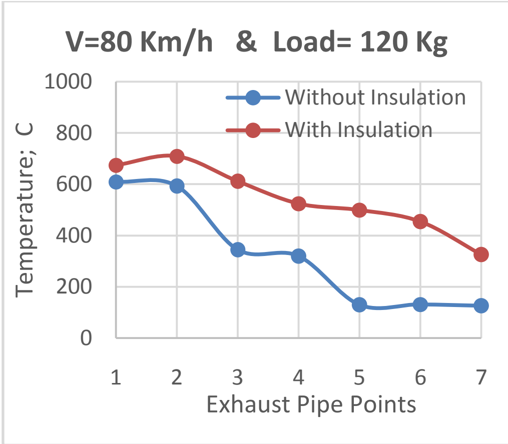

Fig. (14) Temperature distribution at 80 Km/hcar speed and load of 120 Kg.

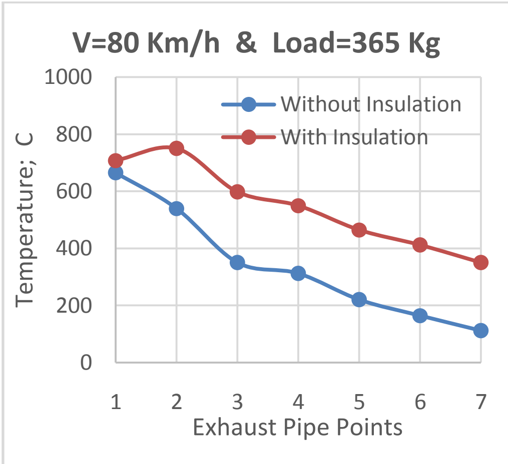

Fig. (15) Temperature distribution at 80 Km/hcar Speed and load of 365 Kg.

Results of analyzed car exhaust gases are summarized in tables 2 and 3.

Table 2: Exhaust gases measurements at zero car speed.

Sample	Gasoline	Uncertainty
O_2	16.9 %	0.79
CO_2	1.16 %	0.05
LEL	0.00 %	0.06
CO	2000 ppm	1.2
SO_2	0.00 ppm	1.6
NOx	14 ppm	0.3

Table 3: Exhaust gases measurements at zero car speed with acceleration.

Sample	Gasoline	Uncertainty
O_2	9.3 %	0.79
CO_2	5.54 %	0.05
LEL	0.00 %	0.06
CO	2000 ppm	1.2
SO_2	0.00 ppm	1.6
NOx	67 ppm	0.3

An attempt has been made to calculate proposed annual energy saving by TEG per kg/s of exhaust gases of Sahin car model, assuming:

1) Specific heat of exhaust gases is nearly equal to that of air corresponding to exhaust gases temperature,

2) TEG efficiency of 15% [13],

3) Electricity cost = 0.07 $/kWh,

4) Car is operated at average of 4 hrs/day, 365 days/year.

Fig. (16) Illustrates annual energy saving upon utilizing TEG to convert the waste heat.

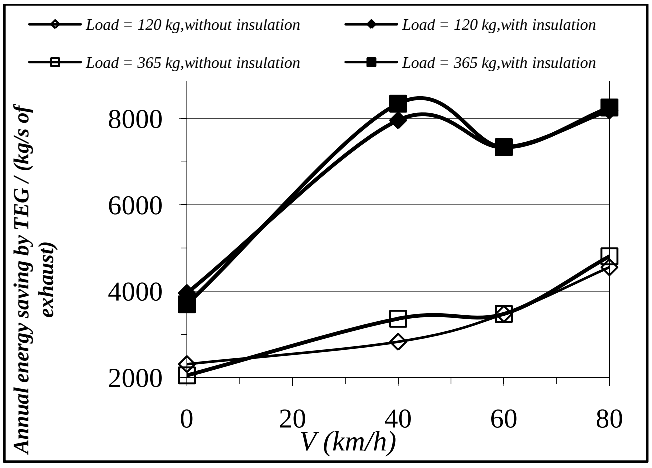

Fig. (15) Annual energy saving by TEG / (kg/s of exhaust) for different car velocities and loads, with and without insulation.

As it may be expected, it may be observed from the figure that the annual energy saving in general increases with increasing velocity, load and with insulation.

5- Conclusions

From the above measurements of temperature distributions and gases analysis we can conclude that for the old car model there is a possibility to add a TEG to enhance the overall engine performance. For the whole temperature range, insulating the exhaust pipe makes the car model more applicable to use TEG.

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