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Waste Heat Recovery System using Thermo Electric Generator

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Abstract—*Our aim is to trap the exhaust heat from an automobile engine and translate it into useful work using thermoelectric generators. The principle followed is Seebeck effect. Thermocouples are assembled with two dissimilar metal wires joined at one end. The most important factor to be considered when selecting a pair of materials is the "thermoelectric difference" between the two materials. The module is Bi-Te based thermoelectric module that can work at the temperature of as high as 330 ˚C heat source continuously and up to 400 ˚C intermittently .The thermoelectric module will generate DC electricity as long as there is a temperature difference across the module. The module is stuck with the high thermal conductivity graphite sheet on its both sides of the ceramic plates to provide low contact thermal resistance; hence you do need not apply thermal grease or other heat transfer compound when you install the module. The graphite sheet can work well in extremely high temperature.From an economic standpoint, we conclude that this process would be economically feasible if energy costs increased by 15%-20%, to about $0.096/kWh.*

1. INTRODUCTION

1.1 Waste Heat Recovery (WHR)

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then “dumped” into the environment even though it could still be reused for some useful and economic purpose. The essential quality of heat is not the amount but rather its “value”. The strategy of recovering this heat depends on temperature of waste heat gases & economics involved.

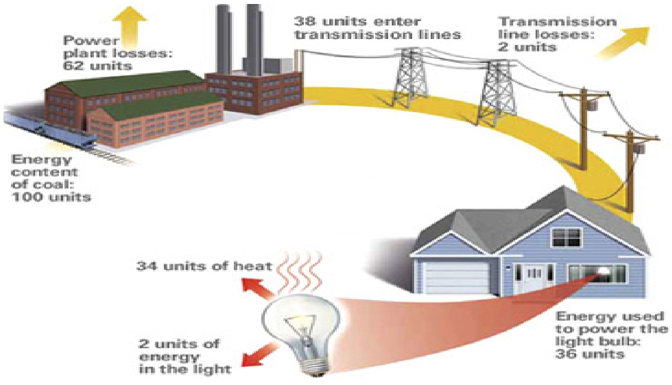


Fig. 1: Energy loss in lighting a bulb

When considering waste heat recovery, the key question is always that of financial justification: "How much money will be saved?" The decision to recover waste heat depends critically on whether the resulting energy cost savings outweigh the installed cost of the proposed waste heat recovery project. As a general rule of thumb, a waste heat recovery project is unlikely to be installed if it’s payback period is longer than two or three years.[1]

1.1.1 How do you set about recovering waste heat?

Waste heat recovery does not always require high capital investment and in some cases little or no cost is involved. This includes:

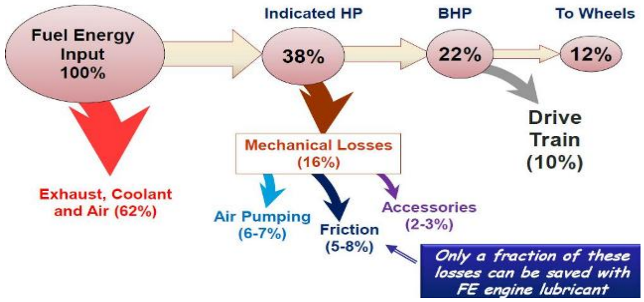


Fig. 2: Fuel Energy Losses

a) Ensuring plant is operating at maximum efficiency;
b) Reducing evaporation and heat loss from open tanks;
c) Optimizing the scheduling and control of operations;
d) Making sure there are no leaks in ducts and pipes;
e) Fitting insulation and ensuring that it is replaced after maintenance.

Classification of waste heat: High Temperature WHR (650-1370), Medium Temperature WHR (230-425), Low Temperature WHR (32-230).

Benefits of WHR: Can be broadly classified in two categories:

Direct Benefits: Recovery of waste heat has a direct effect on the efficiency of the process.

Indirect Benefits:Reduction in pollution, Reduction in equipment sizes, Reduction in auxiliary energy consumption [2].

1.1.2 Development of a WHRSystem

Understanding the process is essential for development of WHR system.

a) Sources and uses of waste heat
b) Upset conditions occurring in the plant due to heat recovery
c) Availability of space & any other constraint, such as dew point occurring in an equipment etc.

1.1.3 Economic Evaluation of WHR System

It is necessary to evaluate selected waste heat recovery system on the basis of financial analysis such as investment, depreciation, payback period, rate of return etc.

1.1.4 TEG Architectures

The first TEG produced has the architecture similar to the one shown in Figure, with vertical structure and single material within each leg. Later, researchers realized that TE material properties are highly temperature dependent, that is to say temperature variation influence TEG performance considerably. The first improvement in the TEG architecture comes with the concept of **segmentation** (or **stack**in some cases) of thermocouple. In this concept, it is suggested that thermocouples should be built with several materials; with each material optimized for the temperature range it is located. With this design philosophy, TEGs could reach higher overall efficiencies than those built with single material within each leg.

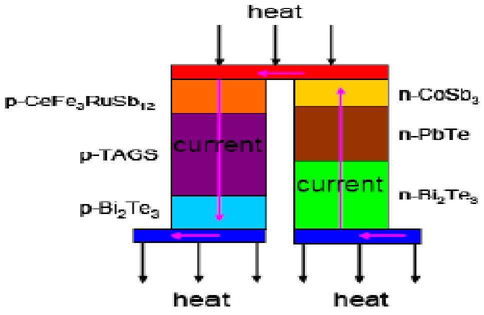


Fig. 3: Vertical TE couple configuration with segmented legs of different total thickness

Crane and Bell went a step further and proposed the concept of horizontal thermocouple configuration. The new configuration allow each p- and n-type element to have different aspect ratios (cross-sectional area divided by thickness) so that each material layer of each element has the highest possible *ZT* for each temperature range, while at the same time, this configuration also increase the design flexibility by allowing p- and n- legs to have different thickness (length).

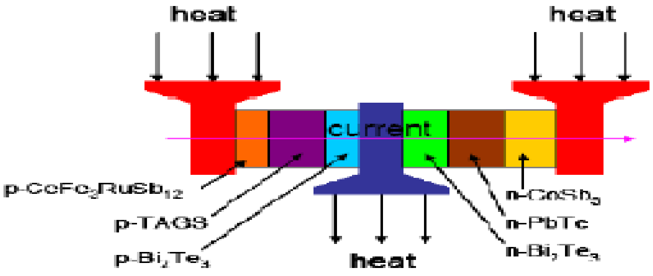


Fig. 4: Horizontal TE couple configuration with segmented legs of different total thickness

1.1.5 Applications of TEG

- The most common application is the use of TEG on gas pipelines.
- TEG'S are primarily used as remote and off-grid power generators for unmanned sites.
- Many space probesgenerate electricity using a TEG whose heat source is a radioactive element.
- Automobiles produce waste heat. Harvesting that heat energy, using a TEG.
- Waste heat is also generated in many other places, such as in industrial processes and in heating (wood stoves, outdoor boilers, cooking, oil and gas fields, pipelines, and remote communication towers).
- Solar cells use only the high frequency part of the radiation, while the low frequency heat energy is wasted.

Advantages:

1) Environmentally friendly.
2) Recycles wasted heat energy.
3) Scalability, meaning that the device can be applied to any size heat source.
4) Reliable source of energy & lowers production cost.
5) TEGs recover heat that occurs naturally, such as heat from geothermal vents, volcanoes, hot springs.
6) TEG's are most efficient when retrieving heat over 250 degrees Celsius.

Disadvantages:

1) Low energy conversion efficiency rate
2) Slow technology Progression
3) Limited Applications
4) Requires relatively constant heat source
5) Lack of customer/industry education about TEG.
6) Generally, TEGs only have an efficiency rate between 5-10%. Also, TEGs require both high thermal resistance and low thermal conductivity. This means it is more difficult for heat to travel across a TEG, causing the poor efficiency rates mentioned above.
7) High investment cost.

2. PRINCIPLE

2.1 The Seebeck Effect

In a thermoelectric material there are free electrons or holes which carry both charge and heat. To a first approximation, the electrons and holes in a thermoelectric semiconductor behave like a gas of charged particles. If a normal (uncharged) gas is placed in a box within a temperature gradient, where one side is cold and the other is hot, the gas molecules at the hot end will move faster than those at the cold end. The faster hot molecules will diffuse further than the cold molecules and so there will be a net buildup of molecules (higher density) at the cold end.

The density gradient will drive the molecules to diffuse back to the hot end. In the steady state, the effect of the density gradient will exactly counteract the effect of the temperature gradient so there is no net flow of molecules. If the molecules are charged, the buildup of charge at the cold end will also produce a repulsive electrostatic force (and therefore electric potential) to push the charges back to the hot end. The electric potential (Voltage) produced by a temperature difference is known as the Seebeck effect and the proportionality constant is called the Seebeck coefficient. If the free charges are positive (the material is p-type), positive charge will build up on the cold which will have a positive potential. Similarly, negative free charges (n-type material) will produce a negative potential at the cold end.

To put it in a simple way, Seebeck effect is the conversion of temperature differences directly into electricity. In the basic version of TEG, the conductor materials used to generate Seebeck effect are two different metals or semiconductors. The term thermo power, or more often, Seebeck coefficient of a material, is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material. The Seebeck coefficient has units of V/K, though it is more practical to use mV/K. The Seebeck coefficient of a material is represented by S (or sometimes σ), and is non-linear as a function of temperature, and dependent on the conductors' absolute temperature, material and molecular structure.

3. CONSTRUCTION

Components Used: Multimeter, Heat Sink, Dc Air Fans, Insulated Materials, Glasswool, Asbestos Lining, Thermal Adhesive, Spacer/Thermal Diffuser.

Construction of a TEG

The power module has large thermal expansion. When the module is running and cycling over large temperature difference, the proper mounting to ensure even pressure applied on module is very important.

3.1.1Hot Side and Cold Side Identification

The modules will generate electricity only if there is a temperature difference across the modules. So, you need to attach one side of the modules to a heat source and the other side to a cool source like heat sink to dissipate the heat coming from heat source through the modules.

Our module is unique & different to others. The modules have cold & hot sides. You should attach the cold side to heat sink or heat exchanger, and hot side to heat Source. The temperature on hot side of the module can work continuously as high as 330°C and intermittently up to 400°C. But the temperature at cold side of the module cannot work properly above 200°C. So, if the mounting is reversed, and the cold side of module is attached to heat source above 200 °C, the module will degrade quickly or fail immediately. So, please ensure hot side attached to heat source is very important.

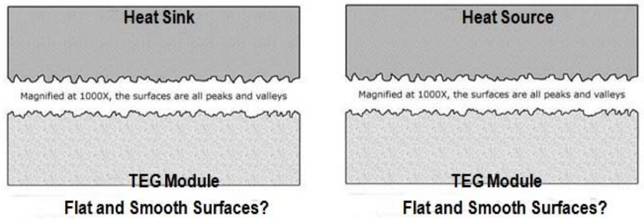


Fig. 5 Microscopic look at surfaces

Temperature range of the TEG Hot side: 60°C±330°C, Maximum400°C

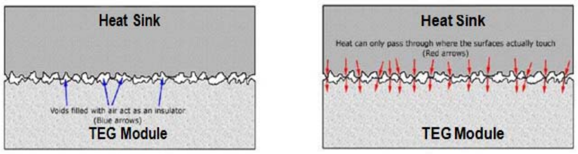
Temperature range of the TEG Cold side: -60 °C ± 180 °C, Maximum 200 °C

3.1.2 Thermal Interface

Even when you have two "flat and smooth" surfaces, they are far from truly flat or smooth. The diagram below shows what's really going on at a microscopic scale.

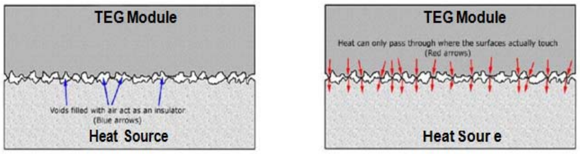
As you can see, the two surfaces may look flat and smooth, but in reality, when examined under magnification, they consist of "hills", "peaks", and "valleys". When these two surfaces are brought into contact with one another, only the peaks make contact. It has been calculated that the average amount of contact between any two smooth surfaces is in reality only 5%. The other 95% are voids!

Surface finish & preparation: As a minimum any surface intended to be part of thermal interface should be flat to 0.001 inches over the entire interface surface and smooth towards surface finish of 3.2 micro inches or better. The interface surface must be thoroughly cleaned, once all machining & polishing is completed. Do not touch the surface with bare hands or allow any contact with other materials.



Contact wit out any TIM

Contact without any TIM



Contact without any TIM

Contact without any TIM

Fig. 6: TIM Contact

3.1.3 Thermal Interface Materials (TIM):

A third party interface material is needed since it is all but impossible to achieve ideal flat & smooth surfaces. The purpose of the TIM is to fill the valleys and gaps with a compressible material that has a much higher thermal conductivity than the air gaps it replaces. This essentially makes the entire interface transfer instead of just where the peaks were contacting.

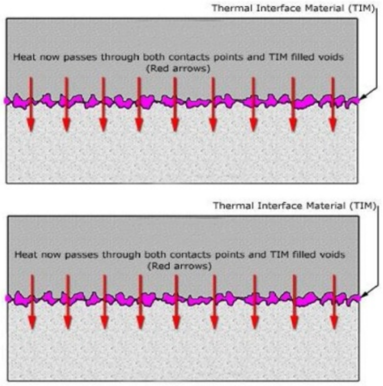


Fig. 7: TIM

3.1.4 Applying the TIM:

Here we prefer to use high thermal conductive graphite sheet which has high thermal conductivity and can operate from -40°C to 400°C. Our TEG module is stuck with such the high thermal conductivity graphite sheet on its both sides ceramic plates to provide low contact thermal resistance, hence you do not need to apply thermal grease or other thermal interface materials when you install the module. The graphite sheet can work well in extremely high temperature.

3.1.5 TEG Mounting

TEGs should be mounted using the compression method. That is, the TEG is compressed between a hot plate and a heat sink that will be cooler. The compression or clamping should be created with stainless steel machine screws on either side of the TEG. See Exploded View and Section View images below.

3.1.6 Screw Position

Locate bolt holes in your assembly such that they are at opposite sides of the center of the TEG between 1.0 mm to 12.7 mm(0.04 to 0.5 inches) from the sides of the TEG. [See first image below] The bolt holes should be in the same plane line as the fins to minimize any heat sink bowing (bending) that might occur.

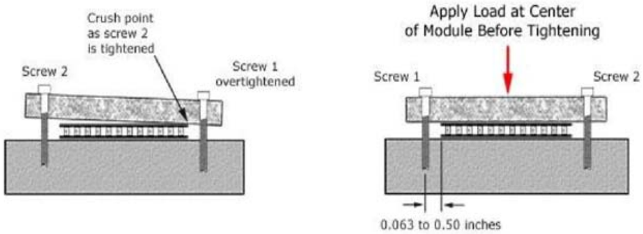


Fig. 8: Screw position

T = (C x D x F x in2) / (no. of screws)
T = torque per screw (in-lbs), C =torque coefficient (0.20 received, 0.15 lubricated), D = nominal screw size (4/40 = 0.112, 6/32 = 0.138, 8/32 = 0.164), F = Force (lbs / in2) in2 = Module surface area (length x width).

3.1.7 Clamping Procedure

Before tightening the screws, apply a light load/force in line with the center of theTEG by using clamp or weight. Make sure the clamp or weights apply the force evenly and at the center. Bolt carefully, by applying torque (tightening the screws) in small increments, and alternating between screws. It is of the utmost importance that the screws are tightened evenly in small increments back and forth. If one screw is over tightened, then the tightening of the second screw may crush the TEG.

Note: If a torque screwdriver is not available, a reasonably accurate pull spring scale attached to the end of an L-shaped hex wrench can be used to determine when the screw torque is reached.[3]

3.2 ASSEMBLY& INSTALLATION OF TEG

Fig. 9: Assembly and Installation of a TEG

4. WORKING

4.1 How Thermoelectric Power Generation Works

The basic concept of thermoelectric Generators TEG's (Seebeck effect) is outlined below to explain to the common man and also Engineers who are not familiar with this technology.

The greater the differential (DT) of the hot side less the cold side, the greater the amount of power (Watts) will be produced. Two critical factors dictate power output:

1) The amount of heat flux that can successfully move through the module.
2) The temperature of the hot side less the temperature of the cold side Delta Temperature (DT).

Great effort must be placed on the heat input design and especially the heat removal design (Cold Side). The better the TEG Generator construction is at moving heat from the hot side to the cold side and dissipating that heat as it moves thru the module array to the cold side the more power will be generated. Unlike solar PV which use large surfaces to generate power. Thermoelectric Seebeck effect modules are designed for very high power densities, on the order of 50 times greater than Solar PV!

Thermoelectric Seebeck Generators using liquid on the cold side perform significantly better then any other method of cooling and **produce significantly more net additional power than the pump consumes.**

For any thermoelectric power generator (TEG), the voltage(V) generated by the TEG is directly proportional to the number of couples (N) and the temperature difference (Delta T) between the top and bottom sides of the TE generator and the Seebeck coefficients of the n and p- type materials.

The standard material we work with is BiTe. The best efficiency that can be achieved with this material is approximately ***6%***. But once the material is placed into a constructed module the efficiency drops to 2 to 3% depending on DT because of thermal and electrical impedance.

No other semiconductor material can perform as well as BiTe as far as efficiency is concerned at temperatures below 300°C.

Other material like PbTe are used but are far less efficient at lower temperatures, and must be used at significantly higher temperatures in the 600°C hot side range and are **commercially available but very expensive.**

We have a 01 amp * module the same size typically 60 mm x 60 mm as a 0.25 amp module in module size, but length or height of the pellet or element determines how much heat can pass thru the module. The ratio of the length compared the actual width x depth determines the overall amperage of the module. As the height of the pellet is shortened ability of heat flux to pass more quickly thru the module allows for greater power generation as long as DT can be maintained. That same 01 amp modules will produce over 4 times the amount of power as the 0.25 amp module. But 4 times the watts will need to pass thru that 01 amp module in order to produce that power. It is imperative that a DT be maintained. The module simply acts as a bridge. The larger the bridge area to length the greater the flow of heat and resulting power output.

Temperature of the hot side is probably the most critical component when considering Thermoelectric Generators. (DT) Delta T needs to be in the 150°C range to get a viable power output from each module. [4]

5. RESULTS AND DISCUSSIONS

5.1 Heat Balance Sheet

A heat balance sheet is an account of heat supplied and heat utilized in various ways in the system. Necessary information concerning the performance of the engine is obtained from the heat balance sheet. The engine should equip with suitable loading arrangement to measure the brake power of the engine. Provisions are also made to measure the amount of air intake.
The heat supplied to the engine is only in the form of fuel
$Q_s = m_f$ x C.V =0.09*41,000 =3,690 KJ/min
=3,690/60=**61.5 KW.**
m_f = mass of fuel used = 5.4/60 = 0.09 kg/min, C.V= Calorific value of fuel in KJ /kg
The various ways in which the heat is utilized are

1. Heat equivalent to brake power of the engine.
2. Heat carried away by the cooling water
3. Heat carried away by the exhaust gases
4. Unaccounted heat losses. [5]

Formulae Used:
Heat equivalent to B.P: The brake power in KW is converted into KJ/min
$Q_{B.P}$ = B.P x 60 = 10.9*60 = 654 KJ/min
= 654/60 =**10.9KW**
=10.9/61.5 =**17.7 %.**
Heat carried away by the cooling water: (Qw)
$Q_w = M_w x CP_w (T_{wo} - T_{wi})$=22*4.186*(38-25)
=1197.19 KJ/min =1197.19/60
=**19.95KW**=19.95/61.5 =**32.5 %.**
M_w = mass of cooling water kg/min,
CP_w= Specific heat of cooling water
=4.186 KJ/kgK.

Heat carried away by the exhaust gases: (Q_g)
$Q_g = m_g CP_g (T_g - T_R)$ =(0.09+2.92)*1.005*(400-30)=1119.26 KJ/min =1119.26/60 =**18.65 KW =**18.65/61.5 =**30.3 %**
m_g= mass of the exhaust gases kg/min, m_a= mass of air consumed = 175.5/60 = 2.92 kg/min, m_f= mass of fuel consumed = 5.4/60 = 0.09 kg/min, C_{pg}=Specific heat of exhaust gases= 1.005 KJ/kgK, T_g= Temperature of exhaust gases = 400^0C, T_R= Room temperature = 30°C.

Unaccounted heat losses

$Q_{un}= Q_s - (Q_{B.P} + Q_w + Q_g)$ in KJ / min =3690(654+1197.9+1119.26) =719.55 KJ/min =719.55/60 =**12 KW**
=12/61.5 =**19.5 %.**
Total heat percentage =17.7+32.5+30.3+19.5 =100%

Procedure

a) Load on the engine, Speed of the engine(Rpm), Time taken for 10 cc of fuel consumption, Manometer readings, Temperature of cooling water at engine inlet and engine outlet in °C, Time taken for collection of 5 lit or 10 lit of cooling water, Room temperature and temperature of exhaust gases
b) From the name plate details, calculate the maximum load that can be applied on the given engine.
c) Check the engine for fuel availability , lubricant and cooling water connection
d) Release the load on engine completely and start the engine with no load condition. Allow the engine to run for few minute to attain the rated speed. Adjust the cooling water flow and maintain steady flow of water. Apply the load, from no load to required load slowly. At required load slowly. At required load note the following.

Result

The test was conducted on the given IC engine and the heat balance sheet was prepared for the particular load.
5.2 Calculation of Efficiency of Thermo Electric Module:
Surface Area $=\pi*d*l = \pi*38*60 =7159\ mm^2 =7.159\ m^2$.
K = 205 W/mK.
$Q_1 = K\ dT/dX$
$= 205*(260-220)7.159*10^{-3}/92*10^{-3}$=638.08 W.

$Q_R= \sigma *A_s*(T_1^4-T_\infty^4)$
$=5.64*10^{-8}*(92*60*4*10^{-6})*(583^4-298^4)$ =134.26 W.

$Q_1 = Q_R + Q_2$
$Q_2 = Q_1 - Q_R =$ 638.08 – 134.26 = 503.82 W.

Q_{LED} = Volt.*Amp. = 9.23*1= 9.23 W**.**
Net Heat Input = 503.82W, Output = 9.23W.
η = 9.23/503.82 =1.83 %. [6]

5.3 Discussions

Table 1: Reading output of TEG

S. No.	Current (Amps)	Voltage (Volts)	Temperature 0C	Power watts
1	0.162	3.82	126	0.618
2	0.182	4.35	147	0.7917
3	0.2	4.72	170	0.944
4	0.29	4.92	182	1.4268
5	0.39	5.05	192	1.9695
6	0.45	5.1	196	2.295
7	0.5	5.15	201	2.575
8	0.6	5.3	204	3.18
9	0.65	5.5	210	3.575
10	0.7	5.95	213	4.165

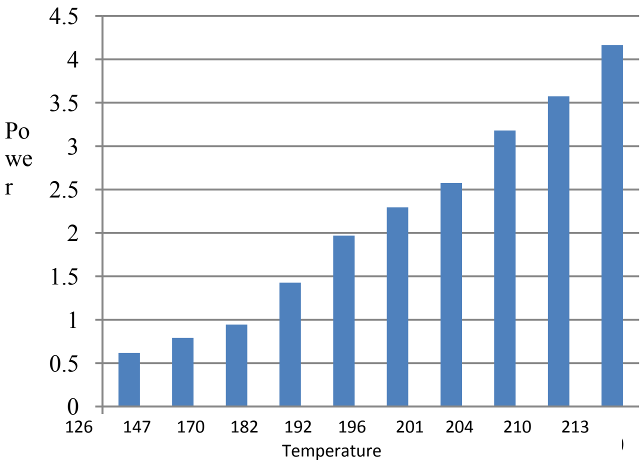


Fig. 10: Graph between Tempt. & Power

6. CONCLUSION

In this work we developed a model for the evaluation of performance of a thermoelectric generator (TEG). The model, which takes into account the thermal contact resistance and the thermal resistance of the two (top-bottom) ceramic plates of the TEG, has been successfully applied into a commercial TEG. The TEG module was capable to deliver 9.2 W of power when the hot-side temperature was 220 C, which is equivalent of about 2 % efficiency. The use of thermoelectric materials in vehicular engines for wasted heat recovery, can help considerably in the world need for energy saving and reduction of pollutants. The allocated power and the temperatures that prevail in the exhaust pipe of an intermediate size car are satisfactory enough for the efficient application of a thermoelectric device. The most advisable place appears to be precisely after the catalyst, where high temperatures prevail. The output power and the efficiency of the device depend on the operational situation of the engine and on the effective designing of the heat exchanger. From the results it appears that even with conventional thermoelectric elements, a thermoelectric device with an output power of around 300 W would be feasible, with a corresponding fuel saving of around 5%. Further improvements in the efficiency of the thermoelectric materials, particularly for high temperature operation, are expected to give a revolutionary impulse to their application in the automotive industry. With the ever increasing economic and social cost of energy production, small thermal to electric power sources for cogeneration and waste heat recovery may someday play a significant role, however small.

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