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Electrical Energy Production in an Automobile Catalytic Converter

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The waste heat available in the catalytic converter (CC) of an IC-engine powered vehicle, from both the exothermic reactions and the sensible heat in the high temperature exhaust gases, is utilized to produce electric power. The electrical energy, produced by a thermoelectric generator (TEG), can then be used to replace or augment existing alternator recharging systems in today's vehicles, or in future hybrid-electric vehicles both to power the vehicle and/or replenish on-board electric energy storage systems. The electrical output of the CC power generator for two sized engines, a 4-cylinder, 1.5L and a 6-cylinder, 3.8L, are modeled for low- and high-speed operation. The modeled engines show that upwards of 11.68kW of energy are available from the engine exhaust, with the smaller engine at low speed producing 2.25kW. This research shows that the CC external surface area and TEG element junction count are suitable to maintain the battery charge. A scheme is presented to replace the vehicle air conditioning system with a solid-state cooler powered by the CC. The high temperatures experienced in the CC can improve overall vehicle efficiency up to 36%.

Nomenclature

A/F	= air-fuel ratio
A_n	= cross-sectional area of n-doped TEG element
A_p	= cross-sectional area of p-doped TEG element
I_{out}	= optimum current produced by TEG junction
L_n	= length of n-doped TEG element
L_p	= length of p-doped TEG element
m'	= resistance ratio, R_o/R, parameter defined by Equation (3)
m_{air}	= mass flow rate of air
m_{fuel}	= mass flow rate of fuel
P_o	= power output of TEG junction
q_h	= heat flow rate to TEG hot junctions
R	= resistance of TEG junction pair
T_c	= temperature of cold junction
T_h	= temperature of hot junction
V_{oc}	= open circuit voltage
Z	= figure of merit
α_n	= Seebeck coefficient of n-doped TEG element
α_p	= Seebeck coefficient of p-doped TEG element
λ_n	= thermal conductivity of n-doped TEG element
λ_p	= thermal conductivity of p-doped TEG element
κ	= thermal conductivity of TEG junction
ρ_n	= electrical resistivity of n-doped TEG element
ρ_p	= electrical resistivity of p-doped TEG element

I. Introduction

Approximately 80% of the energy available in an automobile IC-engine leaves the vehicle as waste heat. After

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combustion and useful work are produced in the engine, a portion of useful energy leaves the exhaust manifold as unburned or partially burned hydrocarbons. The exothermic reactions in the catalytic converter (CC) complete the combustion process to improve overall vehicle emissions, at the expense of producing further waste heat.

Thermoelectric generators (TEGs) are utilized to convert the waste heat in the CC to produce the electrical energy as passive conversion devices. The TEG elements are placed in close proximity to the catalysis bed; the energy from the exothermic reaction heats the hot junctions of the TEGs. The cold junctions of the TEG elements can be cooled by the automobile cooling system, or by the surrounding ambient air. When using TEGs, the junction count can be selected to provide various voltage/current outputs. This will be especially advantageous when automobile electrical systems go to 42V.

Many automotive energy and power systems are being debated, while others are being tested to improve, augment, and/or replace the existing IC-engine powered vehicles used today. It is well known that only about 20% of the energy available in a gallon of fuel is utilized to propel the vehicle. Of the energy lost in the exhaust, 60% leaves the engine as sensible heat and 20% leaves as unburned/partially burned hydrocarbons.[1] The catalytic converter (CC) power generator has been developed to utilize this waste heat to improve the operating efficiency of the vehicle and reduce polluting emissions.[2,3]

The waste energy in the IC-engine exhaust produces electric power for usage in the many electrical/electronic components on today's vehicles. This could include charging the battery, powering daylight running and nighttime lights, radio/video accessories, GPSs, etc. The environment in the CC is especially suited for TEG operation because of the relatively stable temperatures produced during the exothermic conversion of the unburned fuel. In addition, the mass of the catalysis bed in the CC provides a stable thermal source (or capacitor) to convert a portion of the exhaust gases' sensible heat into electrical energy. TEGs are extremely durable devices that produce electrical energy when exposed to a ΔT. The TEGs were developed during the space program to have solid-state reliability as well.

Utilization of the CC to produce electric power from the exhaust stream of the IC-engine benefits vehicle design in two ways. First, to reduce fuel consumption, vehicle weight reduction has been a prime concern. Therefore, by adding minimal equipment to the vehicle (only TEGs in the existing CC), and by using the natural capacitance already available in the CC, minimum weight will be added to recover the waste energy in the exhaust.

Second, the CC is already a standard piece of equipment in most vehicle designs. The augmentation takes place in an add-on device, and the basic configuration of the vehicle body remains untouched. Hence the addition of the auxiliary equipment in the CC is simple. Therefore, automotive manufacturers can make a significant increase in vehicle performance with minimal changes.

For larger engine vehicles, solid-state air conditioning may also be an option to replace vapor compression systems. Vapor compression cooling puts an excessive load on the vehicle, especially in city driving, which wastes fuel and adds to both thermal and emission pollution.

II. Background

The CC is located in the exhaust, usually upstream from the muffler. Figure 1 shows a typical exhaust scheme for today's IC-engine vehicle with a CC. The catalysis bed deteriorates very quickly when operated above 1000^{o}C, hence the mounting of the CC as far from the exhaust manifold as possible.[4] This also benefits many of the more common TEG element materials that are available for systems that operate at temperatures up to 800^{o}C. Not shown in the figure is the muffler, which is located between the CC and the tailpipe exit. The "LOAD" signifies any of the electronic components to be powered by the CC generator.

Note that Figure 1 shows the CC generator with engine coolant flowing through it. This is to enhance the operation of the TEG module. Figure 2 illustrates a typical TEG module. The module consists of p- and n-doped semi-conductor materials which produce an electric potential at the junction of the dissimilar material when both ends of the element are exposed to a temperature difference as shown in the figure.[5] The hot junctions of the TEG elements are in thermal contact with the catalysis bed where the exothermic reaction takes place, and the cold junctions are in thermal contact with the vehicle coolant. The TEG elements operate most favorably when exposed to a constant temperature difference. The vehicle coolant provides a stable thermal sink, and the exothermic reaction in the catalysis bed provides a stable thermal source.

Typically, the catalytic converter has a light-off temperature of about 250^{o}C to 300^{o}C with an operating range of 400^{o}C to 800^{o}C, depending on engine loading. The catalysis bed temperatures change relatively slowly, not following the quick and broad temperature swings that normally occur in the exhaust. With the cooling system operating at 125^{o}C, the temperature difference across the TEG elements can be upwards of 675^{o}C.

Load requirements for today's highly sophisticated electronic/electrical systems on vehicles, including vapor-compression, passenger compartment air conditioning, can consume 2.5kW to 7.5kW, depending on vehicle size and options. For the alternator to maintain the battery charge, 0.60kW up to approximately 1.49kW are needed. A medium sized sedan traveling at 50km/h will produce approximately 3kW to 9kW from the unburned hydrocarbons in the exhaust gases in the catalytic converter. Therefore, the replacement of the alternator with the catalytic generator will improve vehicle-operating mileage considerably.

The benefits of using the CC to produce the electrical energy from the exhaust once again come to light. Alternator size can be reduced, and possibly eliminated, causing an overall reduction in vehicle weight. Hence, downsizing existing equipment will increase vehicle performance by reducing fuel consumption.

III. Highway Driving Mileage Improvement

Typical automobile performance can be used to estimate the fuel savings that will be realized with the CC power generator. During highway driving, the thermal load on the CC can be the maximum, and usually the most stable. Under these operating conditions the electrical power produced in the CC is most suitable to replace the alternator for battery recharge and other on-board electrical energy requirements. This is when the vehicle can experience the most savings and demonstrate the best fuel economy.

The estimated distributed energy requirements for a large sedan traveling on the highway (less accessories) is 32% to maintain steady driving on level ground, 43% for acceleration, and 25% for climbing.[6] The energy needed to operate the accessories at 3000RPM includes the alternator requiring 1.15kW, the radiator fan using 2.24kW, and other smaller devices such as lights, fuel pump, etc., needing approximately 0.75kW. Therefore the total accessory load required from the IC-engine would be about 4.14kW. In addition, to cool the interior of the vehicle, a vapor-compression refrigeration system requires approximately 4.1kW.[7]

For a full sized sedan traveling on the highway at 105km/h (65mph) on level ground, the estimated rolling resistance is 6kW, and the aerodynamic drag is about 8kW. Hence the motive power required by the vehicle is 14kW.[7] Including the accessory load on the IC-engine to power the vehicle, a total of 18.14kW is needed. If the accessory load (including electric radiator fan) can be operated by the exhaust system, the load on the IC-engine will be reduced approximately 23%.

If the exhaust gases can also drive the cooling load, the IC-engine requirements would be reduced from 22.24kW to 14kW, reducing fuel consumption by about 36%. Hence an additional 13% will be saved during the cooling season. The calculations clearly indicate the utility of the CC generator and the useable energy available in the exhaust.

IV. Hypothetical Engine Model

With the many parameters that characterize the operation of an IC-engine and its exhaust profile, two hypothetical engines are modeled, based on actual engine performance, to demonstrate the operation of the CC power generator. For a wide-open throttle, it can be shown that the indicated power output of a theoretical IC-engine is directly proportional to the air consumption for an engine with constant percentage heat loss. In fact, even in an actual engine the air consumption is proportional to indicated power of the engine.[8] Hence this is the premise for developing the thermo-fluid model for the engine. The air consumption is determined from the engine RPM and displacement, then the fuel consumption is predicted, based on the air/fuel (A/F) ratio. From this predicted fuel consumption, the energy in the exhaust is calculated.

The spark-ignition, IC-engines are modeled at two different speeds to cover the full gamut of engines that may be fitted with the generator. These engines also illustrate the full-range operational capability of the CC power generator. As expected, the larger the engine, the greater the amount of energy that is available from the exhaust to generate electric power in the CC.

A 6-cylinder, 3.8L (actually $3791 cm^3$) engine, and a smaller 4-cylinder, 1.5L (actually $1493 cm^3$) engine are used[9] and investigated at two speeds, 1200RPM, and 4500RPM. All of the parameters chosen for the model are considered average for any IC-engine. The engines have an overall efficiency of 25%,[6] from air inlet and fuel mixing to exhaust out the manifold into the CC, and an air/fuel ratio of 15:1, that is, $A/F = m_{air}/m_{fuel}$.[8] At the two modeled engine speeds of 1200RPM and 4500RPM, the exhaust gases enter the CC at 450^oC and 750^oC,[10] with unburned/partially burned hydrocarbons of 4% and 2%,[1] respectively. The conversion efficiency inside the CC of the unburned/partially burned hydrocarbons is 97%.[11]

The inlet air was at standard conditions of one atmosphere and 20°C, and the combustion gas properties used were that of air. The heating value of the fuel is 44MJ/kg.

V. Thermoelectric Generator Model

The theoretical power produced by the TEG modules mounted in the CC is determined from standard TEG equation analysis.[12,13] Heat transfer to the TEG module power generator from the catalytic converter is

$$q_h = \kappa(T_h-T_c) + (|\alpha_n| + |\alpha_p|)T_h I_{out} - \tfrac{1}{2}I^2_{out}R, \qquad (1)$$

where T_h is the temperature at the hot junction of the TEG module in contact with the catalysis bed; T_c is the temperature of the module cold junction in contact with the thermal sink; α_n and α_p are the respective Seebeck coefficients; and I_{out} is the current produced by the TEG pairs. The thermal conductivity κ and the electrical resistance R of the TEG element pairs are defined as

$$\kappa = (\lambda_p A_p/L_p + \lambda_n A_n/L_p) \text{ and } R = (\rho_n L_n/A_n + \rho_p L_p/A_p). \qquad (2)$$

A_n, A_p, L_n, and L_p are the respective cross-sectional areas and lengths of the n-type and p-type TEG materials, and λ_n, λ_p, ρ_n, and ρ_p are the respective thermal conductivities and electrical resistivities of the n-type and p-type TEG materials.

This is for an optimized figure of merit, Z, based on the TEG element's geometry and material properties.[13]

Both the TEG element geometries and the load resistance are optimized to maximize the thermal efficiency of the TEG. To do this, the resistance ratio is defined as $m'=R_o/R$, where R_o is the load resistance. It can then be shown that the optimum resistance ratio is

$$m'=[1+Z(T_h-T_c)/2]^{\frac{1}{2}}. \qquad (3)$$

The equation for the optimum electrical current, I_{out}, produced by the junction is

$$I_{out} = (|\alpha_n| + |\alpha_p|)[T_h-T_c]/R[m' + 1]. \qquad (4)$$

The open circuit voltage for each TEG junction is

$$V_{oc} = (|\alpha_n| + |\alpha_p|)[T_h-T_c]. \qquad (5)$$

The theoretical power from the TEG junction is then determined from:

$$P_o = I^2_{out}R_o. \qquad (6)$$

The minimum number of junctions is determined from the required voltage, and the power output from the CC is based on the available external surface area of the CC that can be utilized for TEG junction mounting. That is, by plugging Equations (2), (3), and (4) into Equation (6), the total power P_o of the CC generator becomes a function of the temperature difference (T_h-T_c) across the TEGs, their material and geometric properties, the length of the TEG elements (for this analysis, $L_n = L_p$,), and the total required surface area of the CC needed for the TEG junction areas. Although the area ratio of the TEG elements, A_n/A_p, is used in the analysis for maximum thermal efficiency, the actual calculations for the total power, P_o, assume that $A_n/A_p \sim 1$. In practice, TEG junctions are typically built with $A_n=A_p$.

VI. Method of Solution and Parameters

The IC-engine performance is determined from the total displacement and the RPMs for the 4-cylinder and 6-cylinder engines, and the exhaust gas flow rates are based on their air pumping capability. Fuel consumption is determined by using an A/F ratio of 15. This engine performance is then utilized to calculate the amount of thermal energy that is available in the exhaust waste stream entering the CC to power the TEG modules.

Typical CC operating temperatures of 450°C and 750°C are used to calculate the temperature difference across the TEG elements. The CC power generator output is 14Vdc for a 12Vdc system. The alternator requirement for the 4-cylinder engine is 0.74kW, and for the 6-cylinder engine is 1.5kW.

The TEG element materials are p- and n-type doped bismuth telluride (BiTe) with constant thermal properties. Although BiTe may not be suitable at the higher temperature range of 750°C in the CC, for the model this is considered acceptable. The TEG elements are 1.5cm x 1.5cm square, and 0.5cm long.

The cold side junction temperature in contact with the coolant is 125°C. For the sensible energy extracted from the hot exhaust gases in the CC, a temperature difference ΔT of 10°C is used.

VII. Results

The calculations for the two engines' performance are shown in Table 1 and Table 2, for speeds of 1200RPM and 4500RPM, respectively. The tables present the data for the air and fuel mass flow rates, as well as the available sensible (sens.) heat and the exothermic energy from combustion (comb) of the unburned hydrocarbons in the exhaust gas stream. Table 1 shows that the minimum amount of energy available from the smaller engine is 2.251kW, which is the sensible energy (0.2094kW) plus the combustion energy (2.046kW) from the unburned hydrocarbons.

	Table 1 -- IC-Engine/CC Performance @ 1200RPM				
	air [kg/s]	fuel [kg/s]	sens.[kW]	comb[kW]	total [kW]
4Cyl./1.5L	0.018	0.0012	0.2094	2.046	2.2514
6Cyl./3.8L	0.0457	0.0031	0.5216	5.205	5.727

At the other end of the spectrum, Table 2 illustrates the large engine operating at high-speed and producing upwards of 11.683kW of electrical power. This would appear to produce enough electrical energy to drive solid-state air conditioning, which will be discussed below.

	Table 2 -- IC-Engine/CC Performance @ 4500RPM				
	air [kg/s]	fuel [kg/s]	sens.[kW]	comb[kW]	total [kW]
4Cyl./1.5L	0.0674	0.0045	0.7692	3.832	4.601
6Cyl./3.8L	0.1713	0.0114	1.955	9.728	11.683

From the tabular values shown in Tables 1 and 2, the total energy is plotted in Figure 3, based on engine RPM. This shows the expected full operating range of the vehicle from highway driving to city driving. The calculated waste energy in the CC of both the 6-cylinder and 4-cylinder engines shows that they could produce enough electric power to drive the expected alternator load under all driving conditions. This waste energy must be matched with the electrical energy conversion capability of the TEG.

Figure 4 illustrates the electric power producing capability of the CC generator based on the amount of surface area on the exterior of the CC available to install the TEGs, as well as the operating temperatures experienced in CCs. For the 6-cylinder engine to meet the alternator requirement of 1.5kW, the CC would need just under 500cm^2 of TEG junctions. In the CC for the 4-cylinder engine, there must be just over 1000cm^2 to produce the needed 0.74kW.

Equation (5) shows that the voltage produced at each junction is a function of (T_h - T_c). Therefore, for the lower CC operating temperature of T_h = 450°C, 102 TEG junctions are required to produce 14Vdc. For the 1.5cm x 1.5cm TEG elements in pairs, a minimum of approximately 460cm^2 is required. At the upper operating temperature limits, 53 junctions would be required, or approximately 240cm^2 needed. Hence Figure 4 well delineates the area required to produce the desired voltage of 14Vdc. The power requirements to replace the alternator are then determined as discussed above.

VIII. Discussion

Figure 3 illustrates the existence of ample waste energy in the exhaust stream gases to operate the electrical accessories on an IC-engine powered vehicle. The smaller engine alternator requirements are less than 1kW, and there are calculated to be over 2kW. The larger vehicle alternator requirement of 1.5kW is well below the 5.7kW produced.

The electric power produced by the modeled TEG elements in Figure 4 illustrates the capability of this simple system without optimizing materials or geometric parameters. The model does show that a larger surface area on the CC is required for the smaller (4-cylinder) engine due to the lower gas loading, which would presumably indicate a smaller vehicle with less room. This is not necessarily bad for the device because accessory requirements are obviously scaled proportionately to the vehicle size. Many variables can still be adjusted to reduce the actual size of the CC area needed as well.

The ΔT drop of $10^{o}C$ of the exhaust gases that was utilized in the CC is a parameter that requires further consideration. Although a ten-degree change is reasonable, there may be practical reasons this cannot be achieved, which will affect the sensible heat portion of the recovered energy. Fortunately, the sensible heat is not that significant compared to the exothermic energy that is recovered, approximately 10% to 15%. However, a CC specifically designed for heat recovery may experience a greater ΔT, resulting in greater energy recovery. This is an area that will be researched further in the development of the model.

The low energy recovery from the sensible heat in the exhaust is another indication of the utility of using the CC. The energy available from the unburned hydrocarbons is about 85% of the total when $\Delta T = 10C$. Creating a greater temperature difference may reduce vehicle performance due to constrictions in the exhaust system. Also, utilizing the CC adds very little mass to the vehicle, only the added TEGs needed for the energy conversion which would be required for any direct energy conversion device of this type.

No discussion is made concerning the thermal efficiency of the TEG modules. This can be calculated using Equations (1) and (6) for the calculated TEG junction count. However, this has not been included as part of this macro study because a micro design of the TEG geometries is first required to maximize or optimize the TEG module output. This is also an area of future research.

Although the premise is that more electrical energy conversion takes place on the highway at higher speeds because of the steady unburned fuel loading in the exhaust gas waste stream, in reality IC-engine vehicles get poorer gas mileage in city traffic. This results in higher surges of fuel during acceleration and more unburned hydrocarbons during deceleration. Hence, more fuel goes through the engine with higher unburned hydrocarbons into the CC. The CC can actually experience higher temperatures during these operating conditions, which will result in a greater $(T_h - T_c)$ across the TEG elements; therefore more electrical energy is produced. This type of stop-and-go driving is much more difficult to model because of the many variables based on personal driving habits, different engine loading, etc. Since the model demonstrates that the CC power generator will operate in the less productive mode of steady driving at various speeds, then the city driving will certainly be successful in producing adequate power to keep the battery charged and drive other accessories.

IX. Conclusions

The exhaust gases from an IC-engine contain more than half the energy that leaves the vehicle as waste heat. The model shows that this energy can be utilized in the catalytic converter to produce at least as much energy as is required by the alternator. In many vehicles, the CC generator can also be used to drive varied electrical/electronic devices now used in these vehicles. In particular, the vapor-compression air conditioning system can be replaced with an all-electric, solid-state cooler that can be powered by the CC generator. Fuel savings in excess of 30% can be realized during the cooling season when air-cooling is desirable.

This initial study clearly demonstrates that the CC is the most suitable component in the automobile exhaust system to recover energy from the hot gases of the IC-engine. The unburned hydrocarbons provide upwards of 85% of the recoverable energy in the gases. The CC is already part of the system, so added weight is minimized for this recovery system. In addition, the CC is already part of the exhaust system, so mechanical changes in the automobile will be minimal.

The model is currently decoupled between the IC-engine operation and the TEGs' electrical energy production. In addition, the details of extracting the thermal energy from within the CC to facilitate better heat transfer to the TEG elements are also required. When the engine thermal model is coupled with the TEG electrical model, parametric studies can be utilized to optimize the heat transfer path from the catalysis bed, through the TEG elements, and into the vehicle cooling system.

Dedication

This research is dedicated to the memory of Joey Parise, a young teen whose early passing from this life precluded the many challenges a father enjoys while raising a son.

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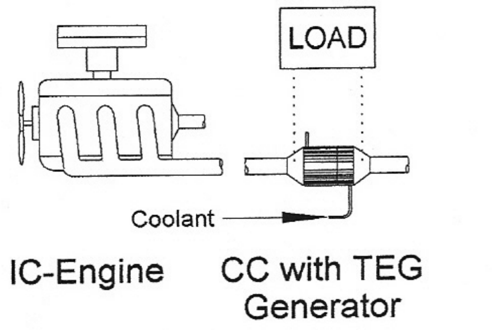

FIGURE 1: IC-Engine with CC Generator

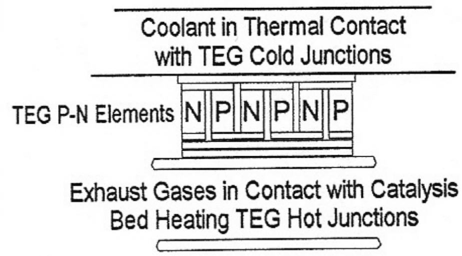

FIGURE 2: CC TEG Module

FIGURE 3: Total Energy Available in Exhaust

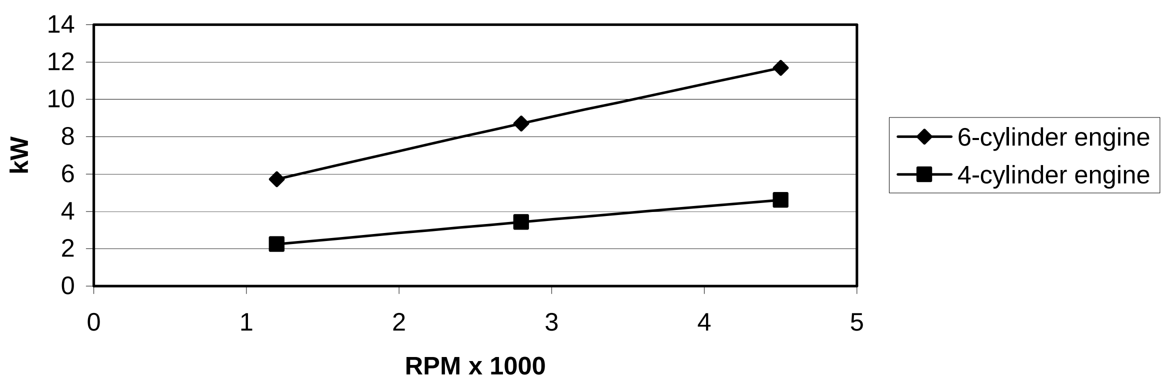

FIGURE 4: TEG Energy Production