Thermoelectric Power Generator by Recovering Heat from Engine Exhaust

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***Abstract—**The main objective of this paper is to recover the waste heat from the automotive engine exhaust into useful electrical energy by using "thermoelectric power generator" .Automotive engines reject a considerable amount of energy to the ambience through the exhaust gas. Significant reduction of engine fuel consumption could be attained by recovering of exhaust heat by using thermoelectric generators. Changing the heat energy of the exhaust gases into electric power would bring measurable advantages. Modern cars equipped with combustion engines tend to have large numbers of electronically controlled components. Contemporary car engines exchange upto 30-40% of heat generated in the process of fuel combustion into useful mechanical work and 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. Therefore, even partial use of the wasted heat would allow a significant increase of the overall combustion engine performance. The observed tendency is to replace mechanical components with the electronic ones. This increases the demand for electric power received through the power supply systems of the vehicle. This tendency will undoubtedly remain at least due to the legal regulations connected with the on-board diagnostic systems, which force a more comprehensive control of operation of the vehicle components in the respect of safety improvement and emission control.*

Keywords—Automotive Thermoelectric Generators; Thermoelectric effect; TE modules

1. INTRODUCTION

Automotive Thermoelectric Generators (ATEG) recovers heat that escapes from a vehicle powered by an internal combustion engine, and generate electricity with the heat. This leads to the significant increase of demand for electric power in the vehicle which has to be generated by the alternator. Chen et al. [3, 5] analyzed the performance of a multi-couple thermoelectric generator with external and internal irreversibility applying an irreversible model. As a result the optimal range of the "parameter for device-design" was determined and the problems concerning maximum power output and maximum efficiency were discussed. Crane and Jackson [8] investigated thermoelectric generators with advanced heat exchangers for waste-heat recovery. Energy conservation statement applied to the hot and cold junctions involves four quantities associated with the various energy transport mechanisms [9].

Esarte et al. [10] used a NTU (Number of Transfer Units)– ε methodology to investigate the influence of fluid flow rate, heat exchanger geometry, fluid properties and inlet temperatures on the electrical power supplied by the thermoelectric generator. A thermal diode [12, 22] is essentially a diode, implemented in a thermoelectric semiconductor, and designed either for energy conversion or for refrigeration. Matsuura et al. and Rowe [15-18] found good expressions for the generator voltage, current and power output. One successful direction of development has been the reduction of lattice thermal conductivity, another the search for so-called "phonon glass electronic crystals" [17, 22], in which it is assumed that crystal structures containing weakly bound atoms or molecules that "rattle" within an atomic cage should conduct heat like a glass, but conduct electricity like a crystal. Rowe and Min [24-28] found a useful approximation for the performance values power output and conversion efficiency considering both thermal and electrical contact effects in the case of isothermal conditions at the hot and cold side of the module. Further studies on the thermoelectric power generation with cylindrical multi-tubes and roll-cake type tubes were carried out in a similar way by Suzuki and Tanaka [32, 33, 35]. Wu [37] accounted for this in his theoretical analysis on waste-heat thermoelectric power generators. An effective internal resistance of a single thermocouple, which is affected by fluid interaction conditions, was used to examine the maximum power output. In practical situations a real thermoelectric generator always combines thermoelectric modules with the specific heat exchangers in very large scale installations to produce useful amounts of electricity from low-grade heat sources [39].

2 TEG

2.1 WORKING OF TEG

When two different conductors are placed in contact, electrons flow from one to the other if the energy levels of the electrons are different in the two materials. The higher energy electrons cross the junction until the energy levels are the same on both sides. The thermoelectric module is made from two conductors whose energy levels change at different rates when the temperature changes. If the junctions are not at the same temperature, there are unequal differences in energy levels across the junctions. Thus, unequal numbers of electrons have to cross the junctions and unequal voltages are established. Since there is a net voltage around the loop, a current will flow.

2.2 LOCATION OF TEG IN AUTOMOTIVE ENGINES

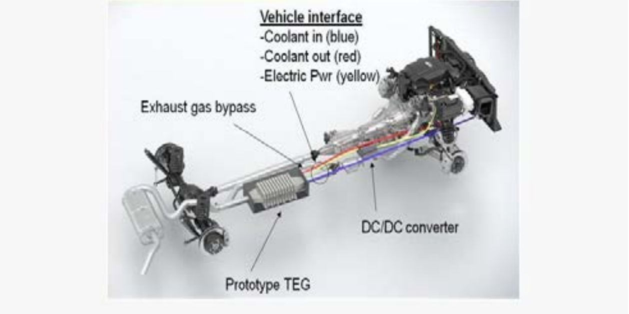

Fig. 1 Prototypes Thermoelectric Generators

The location of the thermoelectric generator is an important factor, decisive of its operability. The TEG generator can be installed on the exhaust pipe immediately between the collector and the catalytic converter or behind the catalytic converter. The heat is absorbed from the exhaust pipe and later converted into electricity by using TEG generator.

2.3 TESTING OF TEG IN AUTOMOTIVE ENGINES

The testing of the temperature distribution was performed at different engine speeds: 2300 and 3300 rpm. The temperatures received at lower engine speed are higher, even though the difference of temperature of the exhaust gases measured for the both engine speeds in front of and behind the heat exchanger is at every engine load point higher for the 3300 rpm by 50°C on average. However, in the first case the coolant flow of 21 l/h was used. At 3300 rpm the flow was 10 times higher, which lead to smaller differences in coolant temperature in front of and behind the coolers, and at the same time to the greater efficiency of heat absorption from exhaust gases.

2.3.1 Low temperature heat sources

Two of the main issues with respect to a sustainable energy supply system are the more efficient usage of energy at all stages along the energy supply chain and the intended use of renewable resources (e.g. geothermal energy). Despite this, we have been wasting enormous amounts of heat from various sources, such as factories, transportation systems and even private houses or public buildings. The waste heat is difficult to use due to its nature of low temperature and low energy density, although the total energy amount is very large. Especially the utilisation of heat which is at too low temperature to drive a turbo generator should be a major task for future energy conversion research and development.

2.3.2 Actual thermal to electrical energy conversion

So far today's electrical energy production is mostly affected by generators based on electromagnetic induction. Reciprocating steam engines, internal combustion engines, and steam and gas turbines have been coupled with such generators in utilizing chemical heat sources such as oil, coal and natural gas and nuclear heat for the production of electrical energy. Renewable energy sources like geothermal energy, solar energy and biomass energy are also being added to the list of heat sources used in modern electric power plants. Furthermore, solar energy provides hydropower indirectly.

The steam-Rankine cycle is the principle exploited for producing electric power from high temperature fluid streams. Gas and steam cogeneration and combined heat and power technologies (CHP) help to improve the electrical and total efficiencies of modern power plants from 35% to about 60%. For the conversion of low temperature heat (below 150°C) e.g. out of geothermal sources, into power, modifications of the steam-Rankine cycle like the Organic–Rankine cycle (ORC) [40] or the Kalina - process [40] are well known possibilities although also with quite limited potential and high costs. For making efficient use of the low temperature waste heat (< 80°C) generated by prime movers such as micro-turbines, internal combustion engines, fuel cells and other electricity and/or heat producing technologies, the energy content of the waste heat must be sufficient to operate equipment found in cogeneration and trigeneration power and energy systems such as absorption chillers, refrigeration applications, heat amplifiers, dehumidifiers, heat pumps for hot water, turbine inlet air cooling and other similar devices.

All these power plants have, however, a common disadvantage; the conversion of thermal energy into electric energy is accomplished by the utilization of moving and wear-subjected machine equipment. The massive bulk of equipment, the irreversibility and complexities of the operation involved in these conversion methods accentuate the desirability of some more direct method for conversion of thermal energy into electrical energy with no moving parts. The degree of directness of a particular conversion process may depend on whether the original form of the energy is chemical, solar or heat. There are several methods known for direct conversion of thermal energy into electricity, such as the thermoelectric conversion, the thermionic conversion, magneto hydrodynamic (MHD) conversion and electro gas dynamic conversion (EGD).

2.3.3 Direct Heat to Electricity Conversion

Efficient Direct Heat to Electricity Conversion (DHEC) has been sought for decades. To date work has focused on two primary directions as mentioned above. There are the thermionic converters, which are only capable of high power densities and efficiency only at temperature in excess of 1000°C, and thermoelectric converters, which operate at low temperature but suffer from low efficiency. The challenge for the future is to create a direct heat to electricity converter of high power and acceptable efficiency, but which is also capable of generating power over a relatively wide range of temperatures. The performance of heat engines and direct conversion devices is limited by the same laws of thermodynamics, and the real application environment therefore plays an important role in determining actual and acceptable performance.

Thermoelectric devices, on which this work is focused, allow the direct conversion of heat from sources like geothermal energy, solar energy or waste heat into electrical power. The main advantages are the low maintenance requirement, the high modularity and the possibility of utilising heat sources over a wide temperature range. Efficient solid state energy conversion based on the Seebeck effect calls for materials with high electrical conductivity σ, high Seebeck coefficient α and low thermal conductivity λ. These properties can be summarized in the maximum ZTs of about at most unity. This gives efficiencies of about 10T −Tot 15 % of the particular Carnot efficiency Carnot = HTH C containing the temperatures TH of the heat source and TC of the sink.

For commercial electricity generation it is necessary to seriously consider generation costs. Thermoelectric suffer from low efficiency; however, when the heat source is nearly free of charge the low generating cost will offset the capital cost of the thermoelectric generator over its lifetime. To minimise the investment cost one would choose to keep the number of thermoelectric modules per kWe low and limit the amount of expensive material used by reducing the thermo element leg length, which leads in general to higher power output, however, to lower efficiency.

3 SOFTWARE

The software used in our project to obtain the schematic layout is MICROSIM.

3.1 PANELISATION

Here the schematic transformed in to the working positive/negative films. The circuit is repeated conveniently to accommodate economically as many circuits as possible in a panel, which can be operated in every sequence of subsequent steps in the PCB process. This is called penalization. For the PTH boards, the next operation is drilling.

3.2 DRILLING

PCB drilling is a state of the art operation. Very small holes are drilled with high speed CNC drilling machines, giving a wall finish with less or no smear or epoxy, required for void free through hole plating.

3.3PLATING

It is the heart of the PCB manufacturing process. The holes drilled in the board are treated both mechanically and chemically before depositing the copper by the electro less copper platting process.

3.4 ETCHING

Once a multiplayer board is drilled and electro less copper deposited, the image available in the form of a film is transferred on to the outside by photo printing using a dry film printing process. The boards are then electrolytic plated on to the circuit pattern with copper and tin.

The tin-plated deposit serves an etch resist when copper in the unwanted area is removed by the conveyor's spray etching machines with chemical etch ants. The etching machines are attached to automatic dosing equipment, which analyses and controls etch ants concentrations.

3.5 SOLDERMASK

Since a PCB design may call for very close spacing between conductors, a solder mask has to be applied on the both sides of the circuitry to avoid the bridging of conductors. The solder mask ink is applied by screening. The ink is dried, exposed to UV, developed in a mild alkaline solution and finally cured by both UV and thermal energy.

3.6 HOT AIR LEVELLING:

After applying the solder mask, the circuit pads are soldered using the hot air levelling process. The bare bodies fluxed and dipped in to a molten solder bath. While removing the board from the solder bath, hot air is blown on both sides of the board through air knives in the machines, leaving the board soldered and levelled. This is one of the common finishes given to the boards. Thus the double sided plated through whole printed circuit board is manufactured and is now ready for the components to be soldered.

4. MODELLING OF THERMOELECTRIC DEVICES AND GENERATORS

Considering the possibility of power generation from low temperature heat sources using thermoelectric devices, necessary tools for the evaluation and optimization of thermoelectric generators and devices shall be prepared. The adaptability of the design of thermoelectric generators permits optimisation to suit the source of thermal energy. For example, if the heat is costly the conversion efficiency will be a main consideration.

In applications where space is at a premium, minimising the volume is a priority, while in applications where the heat is almost for free (waste heat recovery), reducing capital costs becomes a main objective.

In a first step a realistic theoretical model of a large scale thermoelectric power generator will be developed. The model describes the essential elements of a thermoelectric generator: these are the heat transfer system and the thermoelectric devices itself. Here the thermoelectric devices are simplified described as a kind of a "black box" consisting of a large number of thermoelectric couples characterized by its dimensions and average material properties. Linearity and one-dimensionality of temperature and electrical potential distributions are also assumed for above mentioned examinations.

If the validation of the 3D model leads to a good fit with the experimental data a possible usage of the simulation as development tool will be given. Furthermore, the black box assumptions will be compared with the simulation results, checked on compatibility and adapted if required.

Using the proofed large-scale model, procedures to optimise the heat transfer system will be developed. The optimum dimensions of the heat transport system to convey the thermal energy to and off the thermoelectric generator should be explored corresponding to the following objectives:

- Minimising the size of the system (system volume) required to produce one kilowatt electric power
- Maximising the system efficiency or maximizing the electrical power output
- Minimising the number of thermoelectric modules (costs) to produce one kilowatt of electrical power.

Also the influence of module properties on the performance of the TEG will be investigated. Therefore the leg length of the modules and the thermoelectric material properties will be the varied parameters. Last, a representative example for thermoelectric power generation utilizing geothermal heat will be given.

- Summarizing a list of the main tasks of this work is given.
- Approach and list of tasks for this work:
- Evaluation of existing analytical and numerical models from single couples to total thermoelectric generators integrated in heat exchanger units,
- Synergetic combination or integration of models or parts of models to increase the consideration of relevant effects (contact effects, thermal interfaces,…),
- Development of a 3D–finite element model to verify the simplifying assumptions still existing in the analytical/numerical model,
- Validation of the 3-D model with prototype modules,
- Optimization and evaluation studies on large-scale thermoelectric generators with representative example, Relation to other research activities

In cooperation with EMPA Dübendorf the project “Das thermoelektrische Kraftwerk” has been initiated, sponsored by the Swiss Federal Office of Energy.

The main goal of this project is to show the feasibility of a thermoelectric power plant by theoretical considerations and selective experiments. Therefore highly efficient novel thermoelectric materials exhibiting low heat conductivity, small resistivity and large Seebeck coefficients are under development at the Solid State Chemistry and Analyses Group at EMPA Dübendorf.

5. CONCLUSION

The performance of the heat exchanger system forms the basis for continuing the process of design optimization. The designed model of heat exchanger allowed for the utilization of 0.6 to 5.0 kW of exhaust gas energy depending on the operating parameters of the engine. However, the analysis of temperature distribution points out that, upon introduction of specific changes into the design, it is possible to recover even 25 kW of heat energy. Assuming the 5% efficiency of the thermoelectric modules it could allow to obtain the maximum electric power of app. 750 W. This power is comparable to the power of typical alternators used in cars with 1.3 dm3 engine capacity. It should be expected that much greater generator performance can be obtained by building it in the exhaust system of spark-ignition engine types, due to the higher temperatures of exhaust gases.

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