Study of Recovery of Waste Heat From the Exhaust of Automotive Engine

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Abstract

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. One of the most important issues is to develop an efficient heat exchanger which provides optimal recovery of heat from exhaust gases.

The work presents a design and performance measurements of a prototype thermoelectric generator mounted on self-ignition (Diesel) engine. Using the prototype generator as a tool, benchmark studies were performed for improvements in the heat exchanger including determination of temperature distribution and heat flux density.

Introduction

Contemporary car engines exchange app. 30-40% of heat generated in the process of fuel combustion into useful mechanical work. The remaining heat is emitted to the environment through the exhaust gases and the engine cooling systems. Therefore, even partial use of the wasted heat would allow a significant increase of the overall combustion engine performance. 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. 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. This leads to the significant increase of demand for electric power in the vehicle which has to be generated by the alternator. It is predicted that if only 6% of the heat contained in the exhaust gases was changed into electric power, it would allow to lower fuel consumption by 10% due to the decreased waste resulting from the resistance of the alternator drive [1].

Power generation system using the thermoelectric generator should generally consist of the following components: heat exchanger, thermoelectric module, cooling system and DC/DC voltage converter. One of the most important design issues related to the construction of the thermoelectric generator TEG is to develop an efficient heat exchanger, which should provide optimal recovery of heat from exhaust gases.

The heat exchanger delivers heat power received from the exhaust gases to the structure of TE modules. Due to the high speed of the exhaust gases flux, the heat exchange surface area in the heat exchanger should be increased by using the ribbing, grooving and protrusions which would introduce a turbulent flow allowing the increased flow of heat due to convection [4,5]. Heat absorption from gases should occur on a relatively short distance, due to the possibility of increasing the back pressure which would contribute to the changing operating conditions and limiting the engine power.

The paper [4] puts together the comparison of testing designs of thermoelectric generators and exchangers using the exhaust gas heat. On the basis of test results of the thermoelectric generators under research, the design issues can be divided into three groups: a) related to design of the heat exchanger allowing the absorption of the sufficient amount of heat energy from the gases, b) related to the selection of materials for the construction of the TE modules and their installation, c) related to the selection of the appropriate cooling system to ensure significant heat power exchange at low ambient temperature. The development of heat exchange systems could allow for the creation of generators of a relatively large capacity based on the already known thermoelectric materials.

The heat exchangers presented in the paper [4] were created in the direct contact with gases and TE modules. Such a solution requires more space, which limits their potential mounting location. The optimum conditions of TE module operation was ensured by using the ribbing of different surface areas depending on the exhaust gas temperature in the given spot within the exchanger. In this type of designs it is difficult to protect the TE modules from the effect of momentary overheating and to ensure the optimum operating conditions. This leads to the situations in which the modules, based on materials not resistant to high temperature, operate in lower than optimum temperatures at the same time being exposed to damage due to overheating. The transport of heat absorbed from the gases to the TE modules in the paper [6,7] was provided by the carrier medium which was the mixture of noble gases He and Xe. The gas flow monitoring enabled the control of proper operating parameters of the generator. The modules were protected from the possibility of damage due to overheating by the exhaust gases bypass system, in the event of the engine generating excessive heat with the exhaust gases.

The location of the thermoelectric generator is an important factor, decisive of its operability. The TEG generator can be installed on the exhaust pipe [4] immediately behind the collector, between the collector and the catalytic converter or behind the catalytic converter. In the first location the exhaust gas temperature is the highest, allowing the high performance of the generators. The manufacturer's approach to the equipment located in front of the catalytic converter is however negative due to the impact it may have on the operation of the catalytic converter resulting from the decreased temperature of the gases in the outlet. The relatively low range of temperatures in the exhaust system behind the catalytic converter allows for the use of commercially constructed bismuth and tellurium alloy -based modules. However the performance of those modules is low due to the small difference of temperatures allowed for these materials.

The purpose of this paper was to design and test the model thermoelectric generator located behind the catalytic converter. The tests were aimed at determining the distribution of temperature inside the heat exchanger the engine power balance at different RPM and load conditions.

Test bed

The tests were performed using the self-ignition engine of 1.3 dm^3 displacement, with the direct common-rail injection and the Automex eddy-current brake dynamometer (Tab. 1). The engine was controlled by a modified electronic system. The preliminary measurements of the heat exchange mounted on the exhaust system of the engine were conducted on the engine test bed.

Tab. 1 Engine and brake specification.

Engine specification	
Capacity	1.3 dm^3
Engine power	51 kW / 4000 rpm
Torque	180 Nm / 1750 rpm
Cylinders	4
Valves	16
Injection system	common rail
Brake specification	
Type	AMX – 210/100
Maximum power	100 kW
Maximum torque	240 Nm
Maximum rpm	10000 rpm

The tests were performed for the engine parameters including the operating range used in the real operation in road conditions. The authors selected the parameters based on their own experience. Fig. 3 represents the external characteristics of the engine with the operating points marked that were used for testing. To give the full picture of the operating conditions of the generator the measurements were taken in the load characteristics conditions at selected engine speeds, allowing the operation of the heat exchanger in the broad loading range (20-120 Nm).

The research included:

- the measurement of temperatures in the twelve points along the whole length of the heat exchange, on the upper and lower cooler contact surface with the heat exchanger (Fig. 1),
- measurement of the coolant flow through the coolers,
- measurement of the exhaust gas temperatures in front and behind the heat exchanger,
- measurement of fuel consumption,
- measurement of air consumption,
- measurement of received power by the water flowing through the coolers contacting the upper and lower surface of the exchanger.

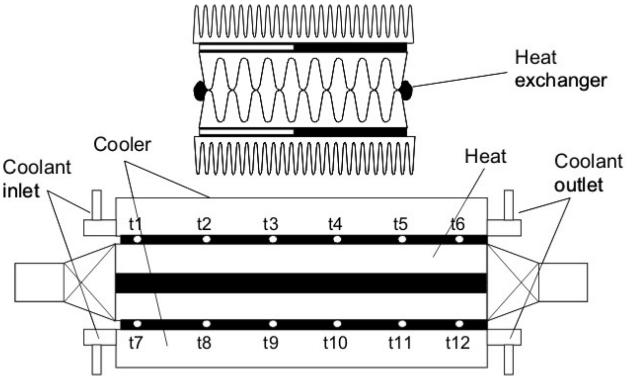

Fig. 1 Cross-section of the thermoelectric generator.

Two variants of heat exchangers were tested. The difference between them was related to the modification of the inlet and outlet cone. The first variant caused the exhaust gases to cool down in the first stage of the flow through the heat exchanger, which resulted in lowering the temperature in the second part of the heat exchanger. The test results presented are for variant two with the improved exhaust gas flow conditions.

Fig. 2 Picture of the thermoelectric generator mounted on exhaust system of self-ignition engine.

In order to compare the temperature distribution on the upper and lower cooler the temperatures were measured at 2300 rpm and 20-120 Nm load. Also the temperature distribution on the lower cooler was presented at engine speeds of 1700 and 3300 rpm. The power received from the exhaust system was compared; the power received by the agent flowing through the cooler was calculated.

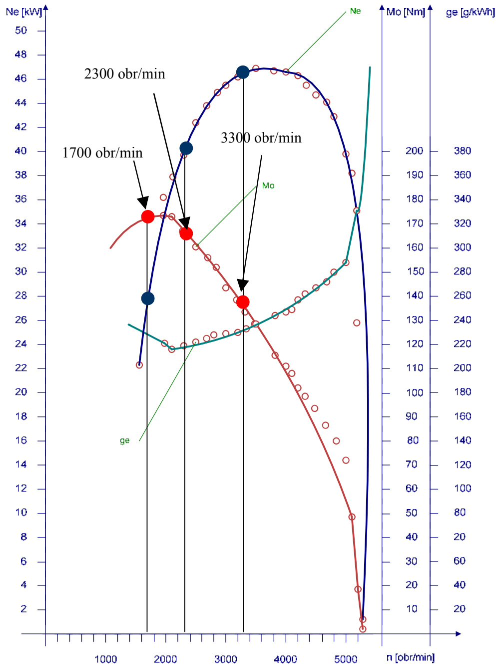

Fig. 3. External characteristics of the 1.3 dm^3 JTD engine

Results

The research shows that the amount of heat contained in the exhaust gases depends on both engine speed and load torque. With parameters corresponding to the maximum engine power of 41 kW (3300 rpm and 120 Nm) the heat obtained in combustion amounts to app. 120 kW and the power contained in the exhaust gases measured behind the catalytic converter is app. 35 kW (Fig. 4).

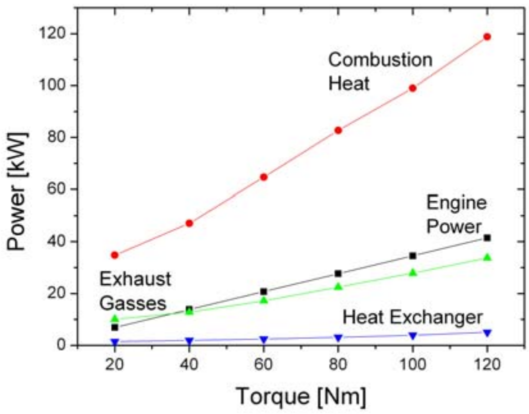

Fig. 4 Balance of energy for 1.3. JTD engine at 3300 rpm and different load.

The distribution of temperatures between the upper and lower cooler and the exchanger differs both in the temperature level and distribution in the particular measurement points. The distribution of temperatures in the bottom cooler is more uniform (Fig. 5). It is related to the lower temperature of the bottom heat exchanger which was connected parallel to the upper exchanger in the water circulation.

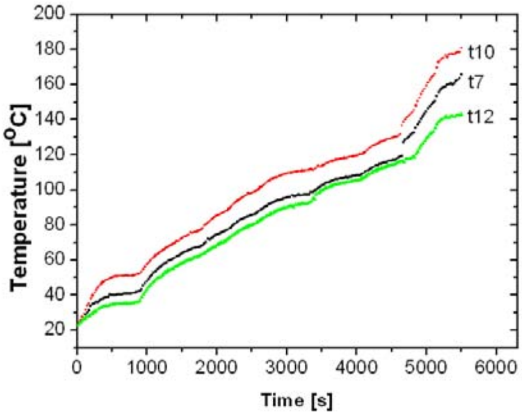

Fig. 5 Temperature distribution in the bottom side of the heat exchanger.

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. This situation is illustrated by Fig. 6, which shows that the most efficient operation of the system was at 3300 rpm.

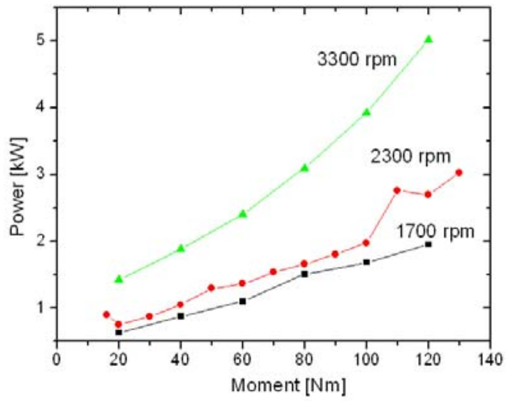

Fig. 6 Heat exchanger power with different engine speed and load.

The heat exchanger built enabled the recuperation of 0.6-3.0 kW for 2300 rpm and 1.4-5.0 kW for 3300 rpm at 20-120 Nm load. The heat exchanger performance obtained for this load range was practically independent of the engine power and amounted to app. 12-14%. Higher performance was obtained for 1700 rpm reaching even 20%.

The observed increase of performance with these parameters results from the smaller stream of exhaust gases and consequently from better conditions of heat exchange. The examination of temperature distribution inside the exhaust system shows that exhaust gases flowing through the exchanger were gradually cooling down by app. 30-60°C which means that a significant portion of the heat power remained in the exhaust gases (Fig.7).

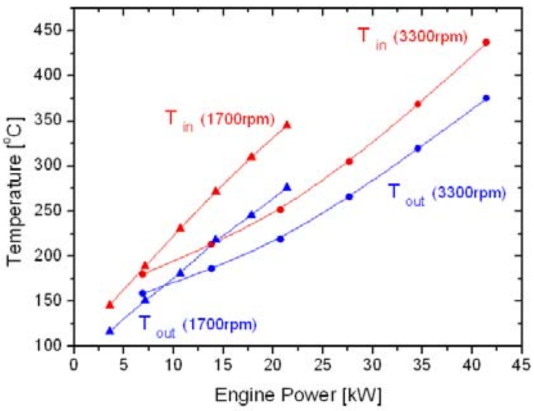

Fig 7. Temperatures before (T_{in}) and after (T_{out}) heat exchanger vs. engine power at 3300 rpm.

It seems that the conditions of heat absorption could be significantly improved by introducing changes to the exchanger design (e.g. extending the active surface, decreasing the gas flow speed). In order to estimate the maximum performance of the heat exchanger the following theoretical calculations have been made assuming constant temperatures of the exhaust gases on the exchanger outlet: 100, 150 and 200°C respectively.

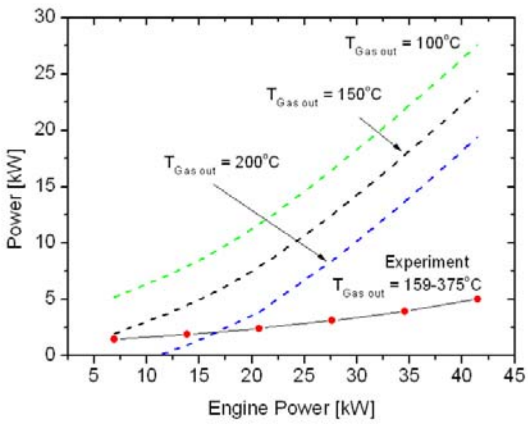

Fig. 8 Experimental and theoretical power of heat exchanger for assumed temperatures behind heat exchanger T_{out} at 3300 rpm.

The results of the calculations (Fig. 8) indicate that with the above assumptions for the engine power above 10 kW it is possible to recuperate from app. 3 to 5 times more of heat power.

Conclusions

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 dm^3 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. This sort of research is going to be continued in the nearest future.

Acknowledgments

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