Selection of the design of a hot heat exchanger of an automotive thermoelectric generator for an urban driving cycle

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Abstract. It is considered for combustion engines to have nearly 60-70\% of fuel energy to be dissipated to the environment by the exhaust gases. Automobile thermoelectric generator (ATEG) application is proved to be a solution for increasing vehicle fuel economy by exhaust gas waste heat recovery. The overall efficiency of ATEG system highly depends on its hot heat exchanger, which is designed to remove heat from the exhaust gases to thermoelectric modules that generate electricity. Intensification of heat transfer in ATEG prototypes is usually achieved by using finning and turbulators. However, the modification of inner side of hot heat exchanger increases the hydraulic resistance of the exhaust system, which adversely affects the power and efficiency of the engine. In this work, we investigate the designs of hot heat exchangers with different configurations of the inner surface and evaluate their impact on the engine power during the modern urban driving cycle.

1. Introduction
One of the main objectives of the automotive industry is to reduce \textit{CO}_2 emissions by more than 4.5\% for passenger cars under urban and country operation conditions. The solution can be achieved by the use of an automotive thermoelectric generator (ATEG) for the exhaust gas waste heat recovery. A high-efficiency hot heat exchanger is an integral part of the automotive thermoelectric generator. Main purpose of hot heat exchanger is increasing the amount of heat energy extracted from engine exhaust gases and its effective transfer to TE modules. It has been demonstrated that the efficiency of ATEG prototype heat exchangers ranged from 40\% to 70\% \cite{1}.

The presence of ATEG in vehicle exhaust system has its own consequences which can negatively affect overall car efficiency. These effects are challenges for automotive thermoelectric industry and we can categorize them into two main types:
1. Increase of hydraulic resistance of the exhaust system
2. Increase in vehicle weight

In order to achieve uniform temperature distribution and higher interface temperature, the optimization of thermal characteristics of the heat exchanger and internal structures are being studied. Increasing the interface temperature by optimizing the internal structure of the heat exchanger will increase the efficiency of the exhaust thermoelectric generator system \cite{2}. The presence of flow-impeding inserts/interal structures results in an adverse increase in backpressure and has a negative effect on
the vehicle engine performance [3]. Fig.1 demonstrates hexagonal prism shaped heat exchangers [4] with different types of internal structures, commonly used for hot heat exchanger designs.

![Figure 1](image)

**Figure 1.** Types of the internal structure of hot heat exchangers: 1) flat walls; 2) oblique fins [5]; 3) longitudinal fins; 4) fins at an angle to the flow; 5) dimpled surface [6]; 6) dimples and turbulizer; 7) corrugation fins; 8) multidirectional fins.

As the main objective is to realize a high overall $CO_2$ reduction for light-duty vehicle in New European Driving Cycle (NEDC) about 4.5% [7], the hot heat exchanger designs should be optimized for urban and extra-urban engine operating conditions.

2. Describing urban operating conditions
The velocity profile imposed by the NEDC used for light-duty vehicle certification is showed in [8]. The Fig. 2 demonstrates a bar chart of engine steady-state modes covering the most used part of the engine map in both urban and extra-urban operating conditions.
3. Modeling ATEG performance

A mathematical model for the operation of the automotive thermoelectric system has been developed [4,9,10,11], which makes it possible to vary design parameters and determine estimative output ATEG characteristics for different vehicle operating conditions.

Figure 3 shows the curves of the increase in power of the internal combustion engine $W_{\text{add}}$, calculated for the hot heat exchangers designs presented in Figure 1 for different engine speeds. The obtained data is made up of electric power generated by ATEG $W_{\text{te}}$ and reduction of load on the onboard electric generator $W_{\text{gen}}$ (1):

$$W_{\text{add}} = W_{\text{te}} + W_{\text{gen}}$$  \hspace{1cm} (1)

**Figure 2.** Bar chart of engine steady-state modes during the NEDC.

**Figure 3.** Curves of the increase in power of the internal combustion engine for designs of heat exchangers presented in Figure 1.
Figure 4 shows the curves of the power loss on the shaft of the internal combustion engine $W_{\text{press}}$ by the hydraulic resistance influence calculated for the designs of heat exchangers shown in Figure 1 for various engine speeds.

Figure 4. Curves of the power loss on the shaft by the hydraulic resistance influence.

Figure 5 shows the graphs of the increase in power on the shaft $W_{\text{mech}}$ taking into account the losses by the hydraulic resistance of the investigated structures of hot heat exchangers (2):

$$W_{\text{mech}} = W_{\text{add}} - W_{\text{press}}$$

(2)

Figure 5. Curves of the increase in power on the shaft.
Analyzing the time spent by the engine in each speed mode corresponding to NEDC, it is possible to estimate the total amount of useful electrical energy generated by ATEG for the described designs of heat exchangers shown in Figure 1 during the cycle (Fig. 6) using the following formula (3):

$$ Q_{sum} = \sum_{i=1,n} \left( W_{mech}^i \cdot \frac{t_i}{3600} \right) $$

(3)

where $n$ - the number of described speeds, $t_i$ - is the time spent by the engine in each speed mode.

![Graph showing amount of useful electrical energy generated by ATEG for different designs of heat exchangers](image)

Figure 6. Amount of useful electrical energy generated by ATEG for the described designs of heat exchangers.

4. Conclusion

In conclusion, it is necessary to mention that we cannot affect consumers operating conditions, so it is necessary to optimize ATEG for NEDC and other known driving cycles, depending on the type of the vehicle. The ideal heat exchanger recovers maximum heat from an engine’s exhaust with minimum pressure drop and shows high thermal uniformity. The heat transfer rate and thermal uniformity of heat exchanger can be improved by optimization of the hot exchanger fin structure. The influence of the hot heat exchanger internal design on the negative reverse pressure and output characteristics of ATEG was studied. The design of the hot exchanger, which ensure the generation of the maximum amount of electric power of the ATEG per driving cycle, were found.
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