Parametric study of air-cooled TEG heat exchanger design for waste heat recovery in heavy-duty vehicle

NV Burnete[1*], **F Mariasiu**[1], **D Moldovanu**[1], **N Burnete**[1], **D Capata**[1], **B Jurchis**[1]

[1]Technical University of Cluj-Napoca, Automotive Engineering and Transports Department, Bd. Muncii 103-105, Cluj-Napoca, Romania

E-mail: nicolae.vlad.burnete@auto.utcluj.ro

Abstract. This study focuses on the influence of different heat exchanger (HX) design parameters like the fin height, fin number, and fin thickness on the performance of an air-cooled exhaust gas thermoelectric generator (TEG). The TEG is considered to be installed on a heavy-duty truck traveling at 85 km/h on the highway thus ensuring the required cooling air for the cold side HX. It was found that the number of fins has the highest influence on the amount of extracted heat and power output of the system, but it also negatively affects the pressure drop. Increasing the fin height improves the pressure drop, but the performance increase is limited. Similarly, increasing the fin thickness provides only limited output improvements, but it also affects the pressure drop. Finally, compared to the hot side HX, the cold side HX has a limited influence on TEG output, but its design is not restricted by the pressure drop.

1. Introduction

Current environmental protection requirements are directly linked to the need for new solutions to reduce pollutant emissions caused by the transport sector. Of all possible ways to reduce pollutant emissions, the currently preferred solution is to employ electric motors and batteries for vehicle propulsion, but current technology still has a major disadvantage in terms of range [1]. However, the main energy source of vehicles (especially heavy-duty vehicles used in freight transport) is still the internal combustion engine (ICE) due to its characteristics and functional performances. If the immediate advantage of using ICEs is given by the range of the vehicles, the big and immediate disadvantages are the low thermal efficiency and the pollutant emission. Consequently, it is necessary to continue researching and developing solutions to increase the efficiency and reduce the environmental impact of ICEs. Since the hot exhaust gases expelled in the atmosphere contain approximately 30 to 40% of the thermal energy resulting from the combustion of the air-fuel mixture, it follows that there is a significant amount of wasted thermal energy which could be harnessed and converted into other types of energy used in the vehicle, thus improving its global energy efficiency [2]. Such a solution is the use of thermoelectric generators (TEG) to directly convert the otherwise wasted thermal energy into electrical energy. The operating principle of TEGs is based on the Seebeck effect which represents the electromotive force generated when a temperature gradient is applied across a thermocouple (TC). A TEG system used for ICE waste heat recovery (WHR) usually consists of several thermoelectric modules (TEMs), arranged in a series or parallel electrical configuration. These systems are usually installed in all ICE areas where heat losses occur, like the exhaust system [3], the exhaust gas recirculation (EGR) system [4], the radiator [5] and the oil pan [6]. Depending on the number and characteristics of the TEMs used to form the TEG, installation location, design etc., the power output values can vary significantly and, to the knowledge of the authors, has not exceeded approximately 1.5 kW. The TEG thermal to electrical energy conversion performance also depends on the temperature difference between the hot and the cold side (temperature gradient) and on the properties of the thermoelectric materials used to manufacture the TEM. Therefore, to achieve high power outputs, researchers usually prefer the combination of high-temperature TEMs with liquid cooling, but this solution has the disadvantage of a more complex and heavier construction. In contrast, this study focuses on the use of an air-cooled (due to vehicle travel) TEG installed on a heavy-duty vehicle traveling at highway speed. A Simulink TEG model (developed and validated in a previous effort of the authors [7]) is used to highlight the influence of the hot and cold side heat exchanger (HX) design parameters on the performance of the device.

2. Methodology

To highlight the influence of various heat exchanger parameters (fin height, fin number and fin thickness) on the performance of the TEG, a numerical study was performed using a model developed by the authors in a previous effort [7]. Compared to the initial model, a slight change has been done to the hot side heat exchanger to allow for the mass flow as an input value instead of the flow velocity. The HX basic design, material (aluminium) and other data remain unchanged. The TEG under study is considered to have a single row of TEMs (perpendicular to the flow direction), electrically connected in series, with the main characteristics given in table 1. With respect to the input data for the hot exhaust gas (mass flow of 0.25 kg/s and temperature of 250 °C) and cooling air (flow velocity of 23.6 m/s and temperature of 20 °C – which is equivalent to a heavy-duty truck traveling on the highway at a speed of 85 km/h and an outside temperature of 20 °C), these were determined from the research of Heber et al. [8]. For the parametric study, two situations were considered: a) the cold side HX design is fixed, while the hot side HX parameters vary according to the data presented in table 2 and b) the hot side HX design is fixed, while the cold side HX parameters vary according to the data presented in table 3.

Table 1. Datasheet of the TEM [9].

Type	GM250-127-28-10
Number of TCs	127
Peak power	28.3 W
Maximum operating temperature	Hot side – 250 °C Cold side – 175 °C

Table 2. Test cases for analysis of hot side heat exchanger design.

	Case 1	Case 2	*Case 3*	Case 4
Fin height (mm)	50	20	35	65
Fin number (-)	80	40	60	100
Fin thickness (mm)	1	0.5	2	3

Table 3. Test cases for analysis of cold side heat exchanger design.

	Case 1	Case 2	*Case 3*	Case 4
Fin height (mm)	60	70	85	100
Fin number (-)	200	150	250	300
Fin thickness (mm)	1	1.5	2	2.5

3. Results and discussions

The simulation results for the hot side HX parametric analysis (table 1) are presented in figures 1 to 10, while for the cold side HX they are presented in figures 11 to 16. In all figures, the naming is formed from the parameter name, the variable symbol (fin height – H, fin number – FN, and fin thickness – Ft) and the variable value (table 1 or 2). Figures 1 to 4 highlight the influence of both the fin height and load resistance ratio on various parameters like the TEG power output (Pel), hot (T_h) and cold (T_c) side temperatures of the TEMs, TEM voltage (V) and TEM current (I). Analysing the results, it was found that increasing the fin hight the TEG output improves. However, the improvement is not linear, and a limit appears to be reached for a fin height of 65 mm. An additional benefit of a larger fin height is a larger hydraulic diameter which leads to a lower pressure drop across the TEG. Considering that manufacturers usually set a limit of 10 mbar or lower for the pressure drop [8], that the TEG design should be lightweight and that the 65 mm fins provide only a slight performance improvement, the optimum fin height appears to be 50 mm. Furthermore, the taller fins also cause a reduction in the HX efficiency because the heat transfer area increase is not proportional with the amount of extracted heat.

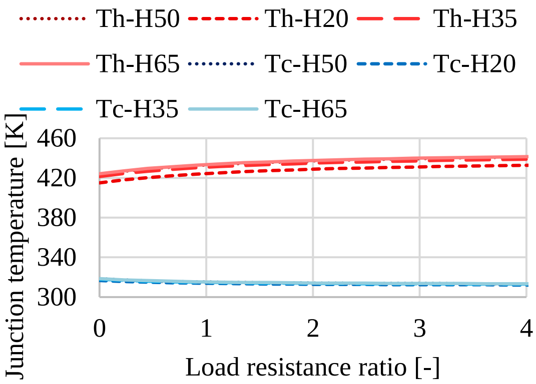

Figure 1. Influence of the fin height on the hot and cold side temperatures of the TEMs.

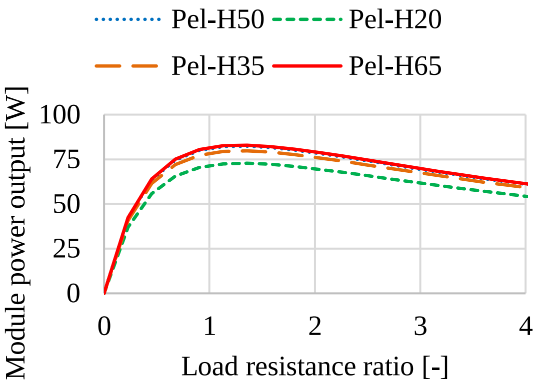

Figure 2. Influence of the fin height on the power output of the TEMs.

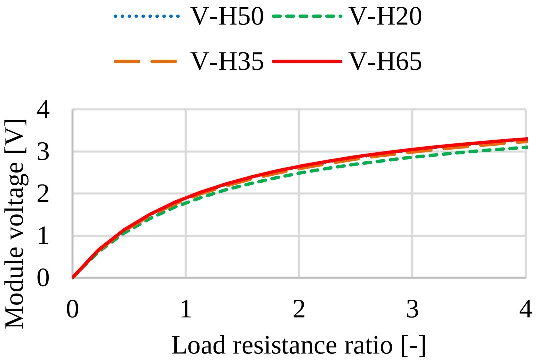

Figure 3. Influence of the fin height on the voltage of one TEM.

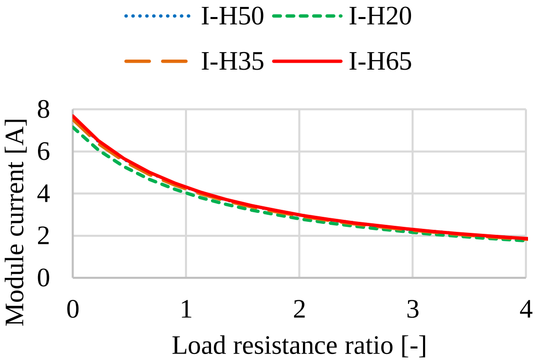

Figure 4. Influence of the fin height on the current of all TEMs.

Compared to the fin height, the number of fins shows a higher influence on the TEG performance. Increasing the fin number from 40 to 100 causes the power output to double, from 47.5 W to 95.4 W, but it also increases the pressure drop from 2.6 mbar to 17.3 mbar. A higher number of fins leads to a higher heat transfer surface, thus benefiting the amount of extracted heat, but a smaller fin spacing (since the HX diameter is fixed) which negatively affects the viscous drag and consequently the pressure drop. As a result, the optimum fin number was found to be 80. Similarly, the fin thickness also affects the heat transfer surface and the fin spacing. However, compared to the number of fins, increasing the fin thickness has a higher impact (negative) on fin spacing than on the area available for heat transfer. Consequently, even if the TEG performance increases with the fin thickness, so does the pressure drop (from 7.6 mbar for a 0.5 mm fin thickness to 32.1 mbar for a 3 mm fin thickness). Therefore, for the present study, the optimum fin thickness was considered 1 mm.

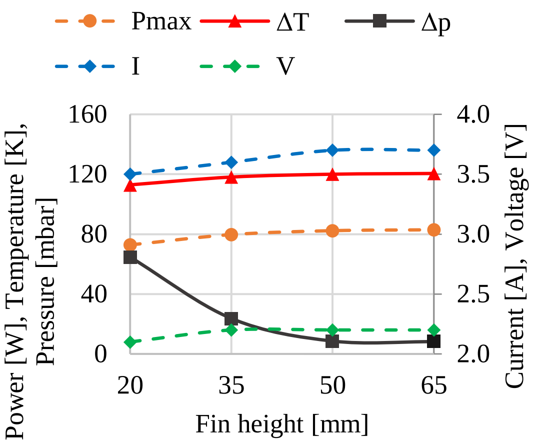

Figure 5. Influence of hot side HX fin height on TEG performance (power (P_{max}), temperature gradient (ΔT), pressure drop (Δp), and TEM current (I) and voltage (V)).

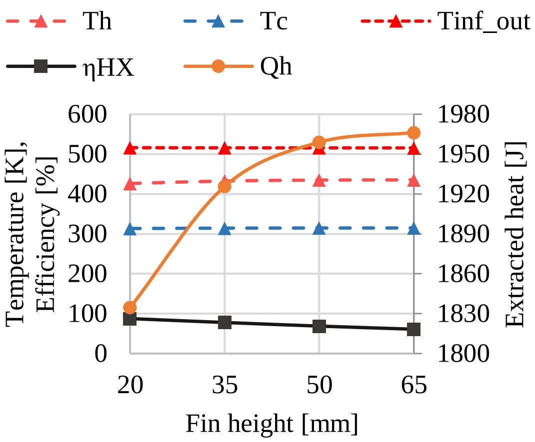

Figure 6. Influence of hot side HX fin height on hot (T_h) and cold (T_c) side temperatures, hot side outlet temperature (T_{inf_out}) and HX performance (extracted heat Q_h and efficiency η_{HX}).

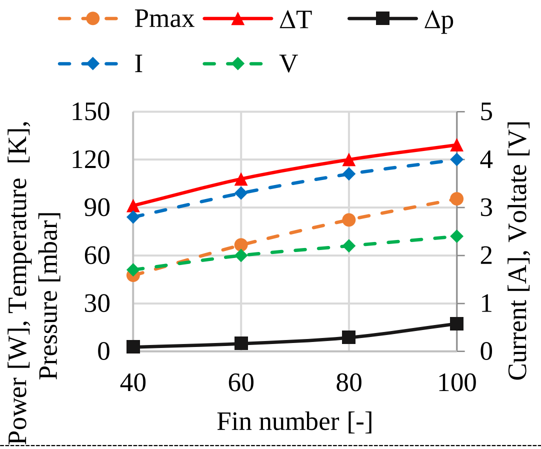

Figure 7. Influence of hot side HX fin number on TEG performance.

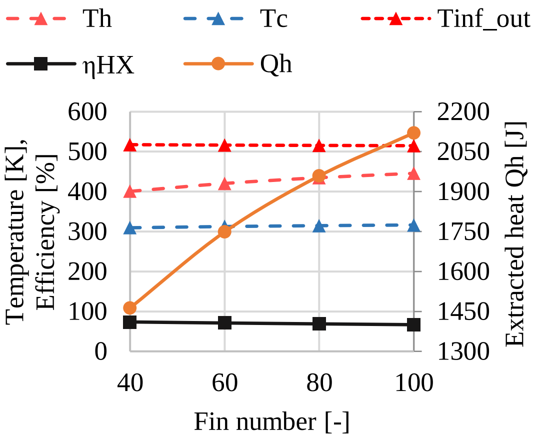

Figure 8. Influence of hot side HX fin number on hot and cold side temperatures, hot side outlet temperature and HX performance.

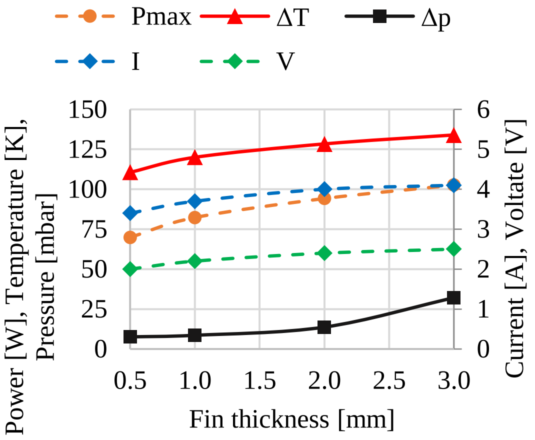

Figure 9. Influence of hot side HX fin thickness on TEG performance.

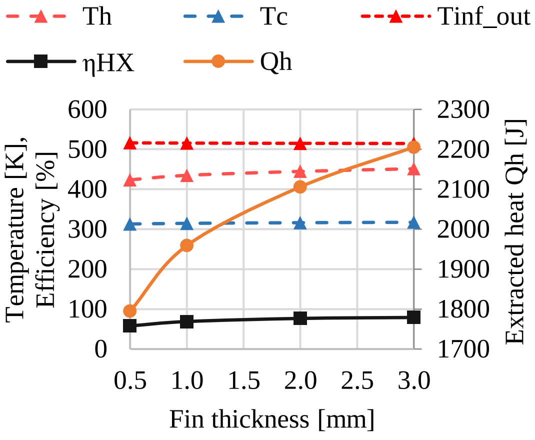

Figure 10. Influence of hot side HX fin thickness on hot and cold side temperatures, hot side outlet temperature and HX performance.

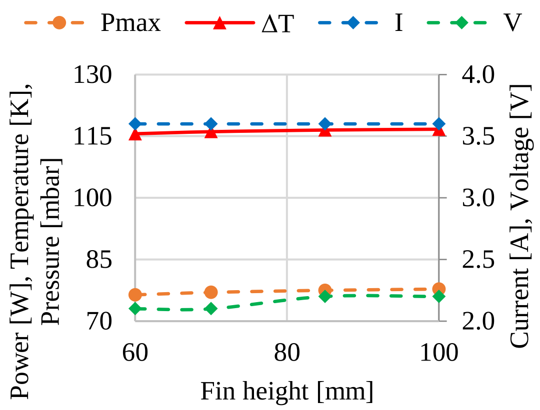

Figure 11. Influence of cold side HX fin height on TEG performance (power (P_{max}), temperature gradient (ΔT), and TEM current (I) and voltage (V))

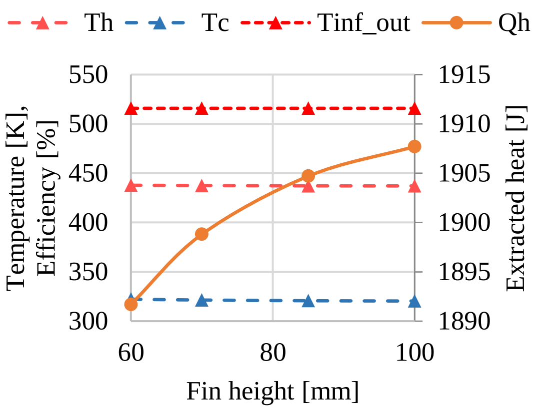

Figure 12. Influence of cold side HX fin height on hot (T_h) and cold (T_c) side temperatures, hot side outlet temperature (T_{inf_out}) and HX performance (extracted heat Q_h)

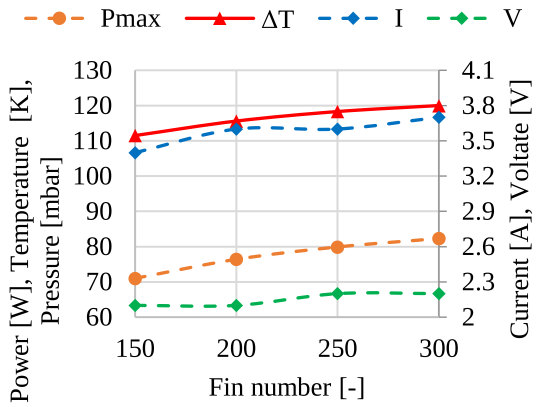

Figure 13. Influence of cold side HX fin number on TEG performance.

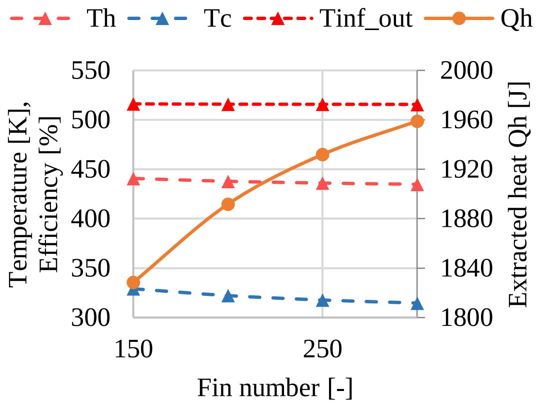

Figure 14. Influence of cold side HX fin number on hot and cold side temperatures, hot side outlet temperature and HX performance.

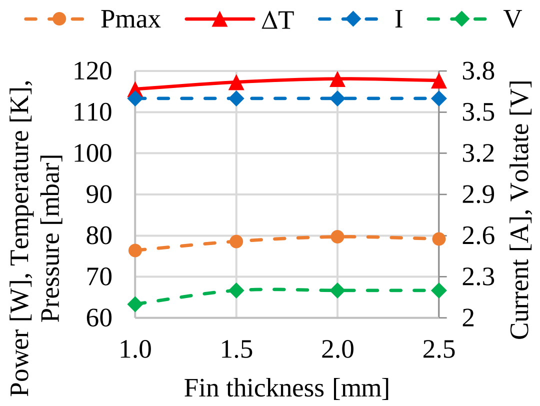

Figure 15. Influence of cold side HX fin thickness on TEG performance.

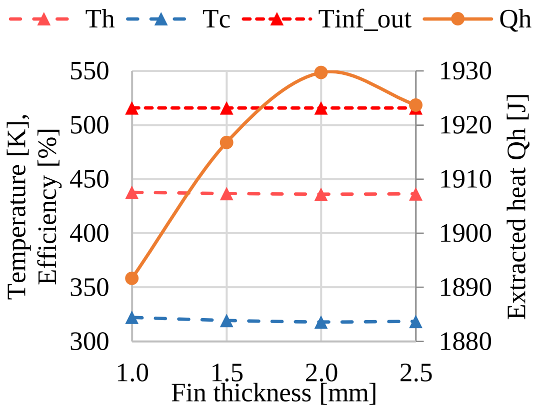

Figure 16. Influence of cold side HX fin thickness on hot and cold side temperatures, hot side outlet temperature and HX performance.

A second set of results (figures 11 to 16) was obtained for a variable cold side HX design, while the hot side HX parameters were kept constant. The analysis of the obtained results has shown that varying the fin height, fin number and fin thickness leads to similar trends to those obtained for the hot side HX. However, the impact of the different designs is significantly smaller. For example, increasing the fin number from 150 to 300 leads caused an increase in the amount of extracted heat of approximately 130 J. In comparison, increasing the fin number from 40 to 100 leads an additional 650 J of extracted heat. Because the cold side HX is not subjected to same restraints as the hot side HX in terms of pressure drop, the design can be optimised for high heat rejection performance. However, care must be taken when opting for design changes that affect the fin spacing (like the fin number and fin thickness) since, at very low fin spacing values the flow is restricted and as a result, the amount of rejected heat drops, thus reducing performance.

4. Conclusions

The present study focused on analysing the influence of the hot and cold side HX design parameters on the performance of an exhaust gas TEG for heavy-duty vehicles, that uses air as cooling fluid. The design variables under consideration were the fin height, fin number, and fin thickness. The analysis of the simulation results has shown that the number of fins has the highest influence on the amount of extracted heat and power output of the system, but it also negatively affects the pressure drop. Increasing the fin height also increases the TEG output and improves the pressure drop, but after a certain value, it reaches a plateau. Of the three variables, fin thickness has the smallest influence on the output, but the highest influence on the pressure drop. Finally, it was found that the cold side HX design has only a limited influence on the TEG output compared to the hot side HX, but, since it is not directly affecting the ICE, it is subjected to fewer design restrictions.

5. References

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Acknowledgements

This paper was supported by the Project POCU/380/6/13/123927 “Entrepreneurial competences and excellence research in doctoral and postdoctoral programs-ANTREDOC”, project co-funded by the European Social Fund.

This research was possible due to the MATLAB-SIMULINK campus-wide license of the Technical University of Cluj-Napoca.