SIMULATION OF A NOVEL HOT-SIDE HEAT EXCHANGER FOR AUTOMOBILE EXHAUST-BASED THERMOELECTRIC GENERATORS USING EFD®

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Abstract

A computer simulation to predict the thermal performance of a novel hot-side heat exchanger for exhaust-based thermoelectric generators (ETEGs) has been developed. This simulation investigates the novel design features of the heat exchanger that can be represented in the implementation of copper-based alloy and innovative geometry. The simulation results can be used explicitly to calculate the output power from any implemented thermoelectric materials. A 3D model for the heat exchanger is introduced. Numerical simulation was implemented using EFD® software package in order to predict the temperature gradient on the heat exchanger surface, as well as the drop in exhaust gas temperature. Several exhaust flowrate and inlet temperature values were adopted to imitate different engine operating conditions and different installation sites respectively. The simulation results were validated against the experimental results from Nissan ETEG prototype, which had comparable dimensions and flow capacity to the proposed ETEG. The results showed that the proposed ETEG has a superior performance compared to Nissan's ETEG in terms of heat exchanger effectiveness and surface temperature gradient. The present design has identified potential to be applied in small size passenger vehicles because of its relatively higher energy density, as well as its compact geometry, which can easily be retrofitted to the exhaust pipe and engine coolant circuit.

Keyword*: Exhaust waste heat recovery, Thermoelectric power generation, Heat exchanger*

1. Introduction

In gasoline fueled vehicles, approximately 40% and 30% of the fuel energy are wasted as heat in the exhaust gas and engine coolant respectively [1]. This huge amount of waste heat has drawn the attention to develop thermoelectric waste heat recovery (TWHR) systems since the early 1960s [2]. However, the efficiency of thermoelectric materials at that time was not satisfactory enough to establish a consistent technology for TWHR systems in automotive applications. With the beginning of the last decade of the twentieth century, a vast revolution in the development of high efficiency thermoelectric materials was provoked by substantial federal R&D funding in the USA in recognition of the potential importance of thermoelectric materials in energy harvesting systems [3] [4]. This revolution provoked the concern about TWHR in automotive systems within the research community worldwide.

Exhaust-based TWHR systems are more convenient and prospect to investigate in gasoline rather than diesel road vehicles [5]. Typically, any ETEG consists of a hot-side heat exchanger, thermoelectric modules, cold-side heat exchanger and assembly elements. The hot-side and cold-side heat exchangers aim to provide the temperature difference across the thermoelectric module in order to produce electricity. While the assembly elements grant a sufficient compressive loading on the thermoelectric modules to eliminate the thermal contact resistance between the module surface and the hot-side and cold-side heat exchangers, see figure 1.

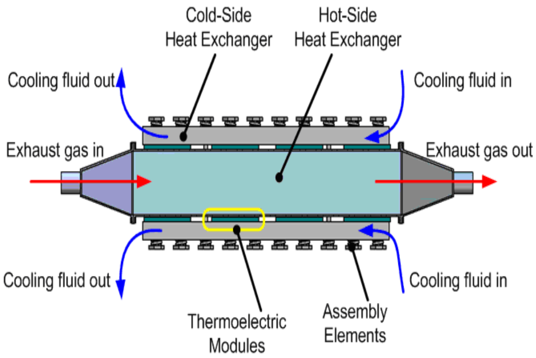


Figure 1: Schematic drawing of a typical ETEG

1.1 Thermoelectric Materials and Modules

A thermoelectric module contains a large number of (P) and (N) doped semiconductors connected electrically in series and thermally in parallel, see figure 2. When these modules are subjected to a temperature gradient, the charge carriers (i.e. electrons and holes) flow from the (N) and (P) type thermoelectric elements respectively; generating an electrical current [6]. For a specific thermoelectric material, the output power and conversion efficiency are functions of the temperature gradient across the module thickness and the thermoelement dimensions [7]. Installation site of the ETEG on the exhaust pipe is mainly governed by the maximum allowable operating temperature of the thermoelectric materials [8]. Iron silicate, Silicon Germanium and Bismuth Telluride are the most popular thermoelectric materials that have been used in automobile TWHR research. Iron silicate and Silicon Germanium can operate at relatively higher temperature value than Bismuth Telluride, while the latter has a higher figure of merit than the first two.

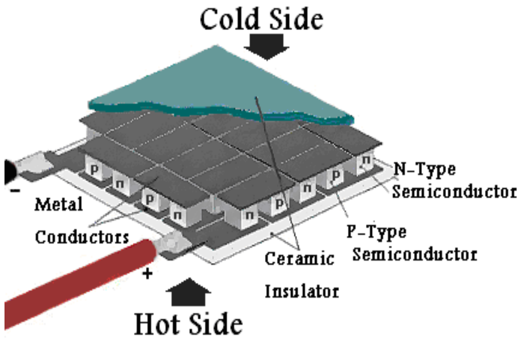


Figure 2. A cutaway drawing of a thermoelectric module showing the (P) and (N) elements

1.2 The Hot-Side Heat Exchanger

The main design requirements for the hot-side heat exchanger are to extract a significant amount of heat from the exhaust, to provide a sufficient hot surface area for mounting the thermoelectric modules, and to avoid any negative effect on the exhaust flow [8]. In the researches described in [9], [10], and [11] the hot side heat exchanger had a sufficient hot surface area for mounting thermoelectric modules. However, in order to provide this surface area, the flow channel cross sectional area was increase significantly. This increase caused the exhaust gas velocity to drop drastically causing the overall heat transfer coefficient to decrease. On the other hand, the hot-side heat exchangers in these researches were fabricated of steel alloys that have relatively low thermal conductivity when compared to copper and aluminum alloys. However, the use of copper and aluminum alloys is definitely disputable because of the sour gases content of exhaust that can corrode the heat exchanger. Several types of heat transfer enhancements, such as internal longitudinal fins and turbulators; were utilized to maintain the exhaust gas velocity at higher values. However, only in the research described in [11] and later in [12], the output power increased from 400 W to more than 1000 W due to the optimization of heat transfer fins in terms of geometry and number.

1.2 The cold-side heat exchanger

In order to achieve the required temperature gradient across the thermoelectric modules, a cold-side heat exchanger is necessary. Engine coolant fluid was used in several researches in aluminum jackets to provide the cold surface for the modules [9] to [14]. In all these researches, water was tapped directly after the radiator outlet to the water jacket on the ETEG assembly. Using engine coolant for cooling ETEG units is useful in decreasing the worming-up time at engine cold start, however, the added cooling load may enforce several modifications to the engine cooling circuit; such as increasing the water pump capacity, radiator size, or cooling fan speed. BMW suggests an independent pre-cooling heat exchanger to supply cold water to the cold-side heat exchanger of the ETEG that is planned to be installed on the BMW series-5 vehicles in 2010 [15]. This pre-cooling heat exchanger drops the ETEG exit water temperature to the same value of the radiator inlet temperature when no ETEG unit installed, thus there will be no modifications required for the radiator, water pump, or cooling fan. An air-based finned heat sink was suggested as a cold-side heat exchanger in lower power ETEG units in [16]. This finned heat sink utilizes the vehicle movement to create turbulence around the staggered aluminum fins to provide a cold surface for the thermoelectric modules. The air-based cold-side heat exchanger does not involve any utilization of the engine coolant, however, its heat capacity (i.e. overall heat transfer coefficient) instigate several disputes about using this type in high power ETEGs.

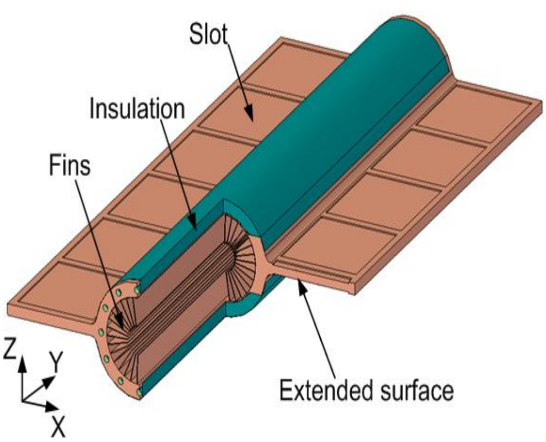
1.4 ETEG Assembly Elements

The thermal contact resistance exists between the thermoelectric module and a heat exchanger surface is considered one of the obstructions of enhancing the thermal efficiency of ETEGs [8]. Thermal Interface Materials and compression springs are used to reduce the effect of thermal contact resistance to the minimum. On the other hand, an efficient electric insulator is essential to isolate the module from any contact with the heat exchanger that might cause a short circuit or even damage to the modules. With the application of highly conductive boron nitride filled thermal grease [17] and ceramic pads, a temperature drop of less than 10 K can be achieved from the hot side to the module, and similar drop from the module to the cold side [18].

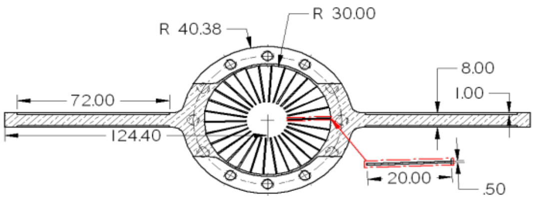
Maximum compressive loading on thermoelectric modules, can be achieved in minimum volume and weight using Belleville springs, they were used by in ETEG researches described in [12] and [13]. The compression load applied by Belleville springs is directly and inversely proportional with the disc thickness cubic and diameter square values respectively [19]; which make these springs require a minimum volume compared to helical springs to provide the same load value.

2. Heat Exchanger Structure And Main Characteristics

In the proposed heat exchanger, the required hot surface is provided through finned-like extended surfaces. The cross sectional area is maintained at 0.89 of the exhaust pipe cross sectional area; in order to avoid any drop in the exhaust gas velocity. The material of the heat exchanger is UNS C81800 cooper alloy, which has a coefficient of thermal conductivity of 218 W/m.K (400% more than the thermal conductivity of carbon steel). A total number of 30 longitudinal fins, each of 20 mm length and 0.5 mm thick, are machined on the internal surface of the heat exchanger to turbulate the exhaust flow as well as to increase the heat transfer area. The two extended surfaces have 1 mm depth slots on both sided to fix the bismuth telluride based thermoelectric modules. The overall length of the heat exchanger is 480 mm. See figure 3 for a detailed drawing of the heat exchanger.



(A)



(B)

Figure 3: **(A)** 3D model of the heat exchanger showing the internal fins and the two extended surfaces with the machined slots for thermoelectric modules **(B)** A sectional side view showing the basic dimensions (in mm) of the heat exchanger.

The exhaust gas enters the heat exchanger in the Y-Axis direction and flows parallel to the internal fins. The insulation on the upper and lower portions of the flow passage restrains the extracted heat to transfer principally to the extended surfaces. A total number of six thermoelectric modules are to be mounted on each side of the two extended surfaces. In this ETEG design, HZ-20 BiTe as thermoelectric materials. Each of these modules can produce 20 W of electric power at a temperature difference of about 211 K between the hot and cold sides of the module at cold-side temperature of 60 ^{o}C [20]. However, this temperature difference is difficult to achieve at different operating conditions.

3. Thermal Performance And Simulation Objectives

The thermal performance characteristics of the heat exchanger are required to meet those necessary for thermoelectric modules. The optimum hot-side temperature of the HZ-20 modules is 200 ^{o}C, while the maximum allowable continuous temperature is 250 ^{o}C [21]. Thus, the heat exchanger is expected to deliver a temperature range between 200 ^{o}C and 250 ^{o}C at different engine operating conditions. In the same time, the temperature difference on the extended surfaces along the X and Y-axis should be minimized as possible. Additionally, the difference between the exhaust temperature and surface temperature should be minimized in order to increase the heat exchanger efficiency [8]. There are two factors control the thermal performance characteristics of the heat exchanger; one is the engine operating condition (i.e. load and speed), two is the installation site of the ETEG along the exhaust pipe. Different engine operating conditions can be simulated by varying the exhaust mass flowrate. Conversely, different ETEG installation site can be simulated by varying the exhaust temperature with each exhaust mass flowrate value. The most important parameter to monitor is the extended surface temperature. Furthermore, it is important to calculate the total temperature and pressure drops through the heat exchanger to study the effect on exhaust flow subsequently.

Although the targeted engine is 2.0 L engine, the simulation is validated against experimental testing results from a 3.0 L engine to prove the novel heat exchanger concept. The heat exchanger geometry is represented through a 3D CAD model, and the simulation is implemented using FEM via EFD® package.

4. Simulation Results And Design Valdation

4.1 Simulation Results

Since the heat exchanger is symmetric around Y-axis, the computational domain includes only one-half of the heat exchanger in order to reduce the simulation processing time. The extended surface geometry has been simplified to exclude the slots for mounting thermoelectric modules, thus, their thickness has been reduced to 6 mm each. Air properties were used instead of exhaust properties to simplify the solution, and steady-state condition is assumed. The boundary conditions are summarized in table 1.

Problem Type	Heat transfer in solids	Yes
	Internal flow analysis	Yes
	Reference axis of CGS	Y
Default Material	Material name	UNS C81800
	Density	8620 Kg/m3
	Thermal conductivity	218 W/m.K
	Roughness	50 µm
Default Fluid	Fluid name	Air
	Molecular weight	28.966
	Thermal conductivity	0.027 W/m.K
Wall Conditions	Heat transfer coefficient	8 W/m^2.K
	External temperature	303 K

Table 1. Boundary conditions of the simulations process

In order to study the effect of engine operating condition and installation site of ETEG; air mass flowrate has been investigated at 0.03, 0.044 and 0.058 Kg/s at multiple inlet temperature values. At the maximum flowrate and temperature values, the temperature distribution on the extended surfaces has been found to be as in figure 4.

The temperature difference between the inlet and outlet of the heat exchanger ranged between 34.5 and 81.75 K for the same flowrate value of 0.03 Kg/s at different inlet temperatures. This difference reached 119.86 K at air flowrate and inlet temperature values of 0.058 and 850 K respectively, see figure 5. On the other hand, the temperature difference along the centerline of each extended surface ranged between 9.1 and 22.54 K for the same flowrate value of 0.03 Kg/s at different inlet temperatures.

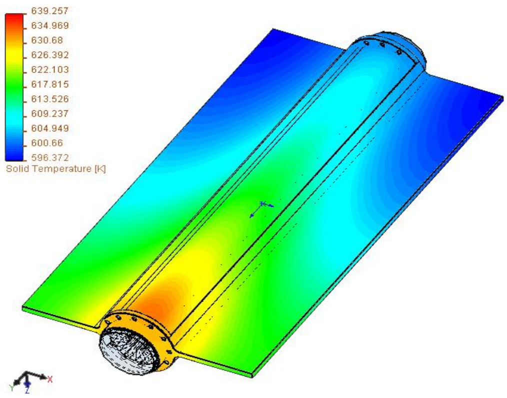


Figure 4. Solid temperature distribution at air flowrate of 0.058 Kg/s and inlet temperature of 800 K

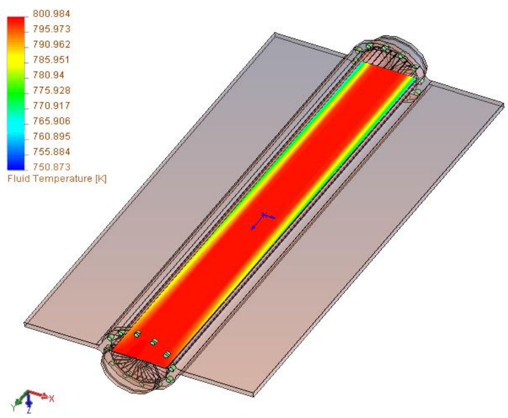


Figure 5. A cut plot showing air temperature distribution at air flowrate of 0.058 Kg/s and inlet temperature of 800 K *(Scale is enlarged to show the distribution pattern)*

4.2 Validation of Heat Exchanger Design

The ETEG proposed by Nissan research center in 1998 [22] had a hot-side heat exchanger fabricated of SUS304 steel alloy[1]. This alloy has a low thermal conductivity at 21.5 W/m.K at 500 K [23]. The ETEG overall dimensions were 440 × 180 × 70 mm3 and the overall weight was 14.5 kg. The SiGe thermoelectric modules were mounted between steel hot-side heat exchanger and two water-cooled jackets made of aluminum. The modules were arranged in twelve blocks (M1 to M12). See Figure 6.

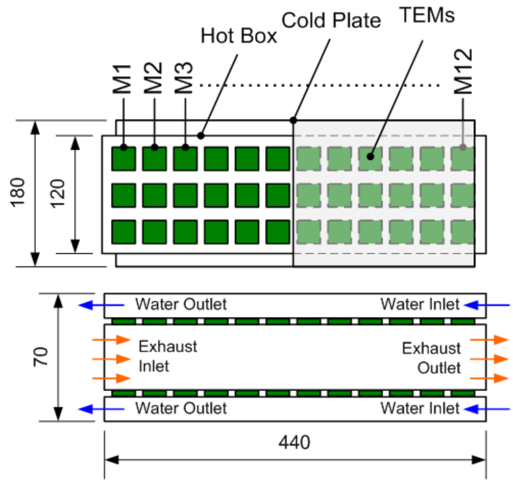


Figure 6: Schematic of Nissan ETEG showing the basic dimensions in mm

The measurements have been performed under the condition corresponding to 60km/hr hill climb mode of 3000cc gasoline engine vehicle. A combustor bench was utilized for simulating the engine exhaust at the desired operating condition and for measuring temperature distribution in the generator and for evaluating electric power of the generator. The exhaust gas flow produced by the combustor is divided into two lines. The one line is connected to the generator, and the other to the bypass line. The temperature and the flux of exhaust gas from the combustor can be controlled by changing the ratio of air to fuel (A/F) and the flow rate of air blowing into the combustor. There is the orifice diameter at the inlet of each line, then

[1] Chemical composition of SUS304: Fe, <0.08% C, 17.5-20% Cr, 8-11% Ni, <2% Mn, <1% Si, <0.045% P, <0.03% S [24]

the flux of exhaust gas through the generator is controlled by adjusting them, see Figure 7.

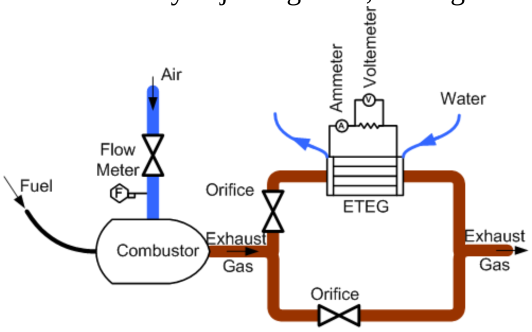


Figure 7: Schematic shows the combustor test bench used to simulate the engine exhaust for the Nissan ETEG testing

The exhaust mass flowrate at the testing condition was 0.058 Kg/s while the inlet temperature was 850 K. These experimental conditions are similar to the input data given to the simulation model at maximum assumed operating point. At these conditions, temperature distribution for exhaust and hot surface as in figure 8 were experimentally measured.

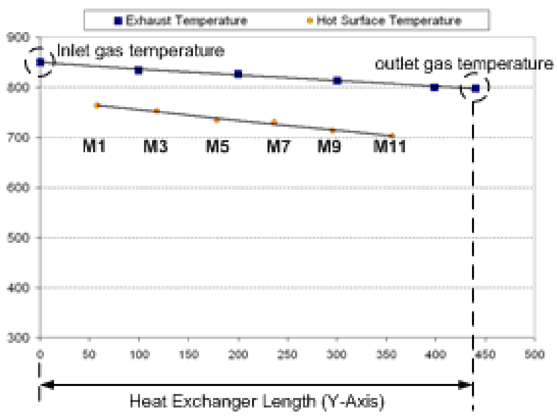


Figure 8. Exhaust gas and heat exchanger surface temperature distribution for the Nissan ETEG derived from experimental testing

The temperature difference between the inlet and exit points of the exhaust gas was 52.6 K while the corresponding temperature difference between the first and eleventh module rows was 60.6 K. This large temperature difference at the hot surface causes inefficiency in power generation, and causes high fluctuation in voltage when the engine transmits from one to another operating condition. In the present simulation, the temperature difference at the hot surface is decreased to 29.1 K between the center of the first and sixth modules at each side of the extended surfaces. While the difference in exhaust temperature between the inlet and outlet points of the heat exchanger is increased to 119.86 K. This increase indicates an increase in the overall heat transfer coefficient almost equals to double. The increase in the overall heat transfer coefficient can be reasonably understood because of the high thermal conductivity of the heat exchanger material, as well as the miniaturized cross sectional flow passage Figure 9 shows a graphical comparison between the thermal performance predicted by the simulation model and the experimental results of Nissan ETEG.

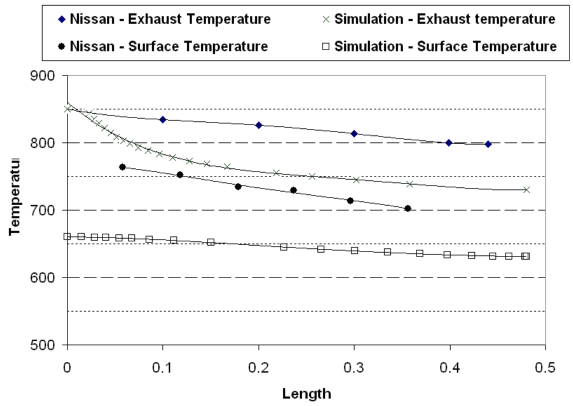


Figure 9. Comparison between the thermal performance of the simulated heat exchanger and the experimental results of Nissan ETEG.

5. Conclusion

A novel hot-side heat exchanger for exhaust-based thermoelectric generators is presented in this paper. The heat exchanger design encounters two main issues in improving the thermal performance of ETEGs. The first issue is the heat exchanger material; this design utilized highly conductive copper alloy, which has a high resistance for chemical and corrosive reaction as well. The second issue is the thermal and hydraulic design of the heat exchanger. The present design has a flow cross sectional area smaller than the exhaust pipe, and two extended surfaces for mounting the modules. These two innovative design features has resulted in better thermal performance when submitting the heat exchanger 3D model to EFD® simulation software. The simulation results were validated against the experimental data acquired by Nissan Motors for their ETEG. The results show that the thermal energy extracted through the presented design is almost two times higher than the thermal energy extracted through the Nissan ETEG. Additionaly, the drop in surface temperature for the present design is almost half of the drop in surface temperature for Nissan ETEG, which is more likely to provide stable voltage, especially when transmitting from one to another engine operating point.

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