Experimental Investigation of the Performance of Different Heat Exchanger Profiles in the Waste Heat Recovery System with Thermoelectric Generator for Automobile Exhaust Systems

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Abstract

In internal combustion engines, the most waste heat is emitted from exhaust and cooling systems. Thermoelectric generators are an important alternative for recycling waste energy in the exhaust systems of internal combustion engines. In thermoelectric generators, the cooling of the heat discharge surfaces is very important for module performance. In this study, two different cooling profiles to be used for waste heat recycling in the exhaust systems of internal combustion engines were designed and performance tests were carried out in different thermal conditions. Maximum V=12,5 V voltage was obtained from the designed system ("B" profile) at T_h=250°C, ΔT=20 °C, R_L=55 Ω load resistance and maximum0,46 A current was obtained at R_L=5 Ω load resistance.

Keywords - *waste heat, thermoelectric, internal combustion engine, exhaustsystem, air cooling*

I. INTRODUCTION

As a device for directly converting thermal energy into electrical energy based on the Seebeck effect, the thermoelectric generator (TEG) can be used in the case of waste heat recovery thanks to its many advantages like no moving mechanical parts, long-lived, quiet, environmentally friendly and requiring little maintenance [1].On the recovery of waste heat of internal combustion engines, especially on cooling and exhaust systems has been studied. The importance of using thermoelectric generators for recovery purposes in the internal combustion engines is increasing day by day. [2].

A. TEG Module Use in Exhaust System

A lot of research has been conducted about using TEGs for power generation by recovering automobile exhaust system as a heat source. Having tested the performance of 16 HZ-20 generators which were connected in series and placed in automobile exhaust, Thacher et al. [3] found that output power was limited by the heat exchanger of hot side and the maximum allowed operating temperature.

Having built a one-dimensional thermal resistance model to predict the behaviour of TE system applied in exhaust pipe and radiator of an automobile, Hsiao et al. [4] reported that the temperature difference across the TEG and the output power increased as the engine speed or the coolant temperature increased, and the performance of the TEG placed on the exhaust pipe was better than on the radiator.

Investigating the behaviour of TEGs applied on the exhaust pipe of an automobile, Anatychuk et al. [5] reported that the temperature distribution along the TEGs was exponential. They concluded that the half of the TEGs operated under high temperature conditions so that using low-temperature TEGs was not appropriate in the tested system.

In 1988, Birholz et al. [6] presented the first TEG's application on the automobile. In this research, a single TEG unit using $FeSi_2$ as material was adopted to produce 1 W electric power. Bass et al. [7–11] applied an array with 72 pieces of TEG on a diesel truck. By maintaining 230 °C and 30 °C at hot and cold sides of TEGs respectively, energy conversion efficiency of 4.5 % was achieved. Kobayashi et al. [12] used the same amount of SiGe TEGs on a 3000 c.c. petrol engine vehicle. A rectangular section of exhaust pipe was used as the hot source and attached by one side of TEG. On the other side of TEG, a water cooling system was used as a heat sink. At 60 km/h vehicle speed, the exhaust temperature was 1141 °C, and the temperature difference on TEG was 563 °C. The maximum power generated from a single TEG was 1.2 W at 0.7 V with 0.9% thermal efficiency.

BMW company started the works on the use of TEGs in 2007. The first generation systems are recycle systems that produced a maximum of 200 W of electric power. Vehicles with this system were first launched in 2008. It became possible to produce vehicles generating 600 W electric power in the exhaust system after diminishing the size and weight of TEGs and the introduction of new semiconductor materials. In 2009, the BMW Group designed a system in which TEGs were placed under the vehicle into the EGR radiator as a total conversion system. The system produced 250 W electric power according to the test results, reducing CO2 and fuel consumption by 2%.

B. Main Frame Design of Recycle System

The number, dimensions and dimensional compatibility with the exhaust system of modules to be used in dimensioning the heat exchanger are taken into account.

Module dimensions: 40x40x3 mm

$L_{mod\,,t}$= Total module length (mm)

$$L_{mod\,,t} = w_{mod}\, N_{mod}$$

$W_{mod\,,t}$= Total module width (mm)

$$W_{mod\,,t} = w_{mod}\, N_{mod\,,1}$$

A_{mod} = One side area of the modules (mm^2)

$$A_{mod} = L_{mod\,,t} W_{mod\,,t}$$

βlw= Length-width ratio of the modules

$$\beta lw = \frac{L_{mod\,,t}}{W_{mod\,,t}}$$

$A_{mod\,,t}$= Total surface area of the modules (mm^2)

$$A_{mod\,,t} = \gamma A_{mod}$$

L_g= TEGrecyclemain frame length (mm)

$$L_g = \sqrt{\beta lw A_{mod\,,t}}$$

W_g= TEGrecyclemain framewidth (mm)

$$W_g = \sqrt{\left({}^{1}\!/_{\beta lw}\right) A_{mod}}$$

C. Design of Cooling Fins

Rectangular geometry fins have widespread use due to design and manufacturing convenience. Taking into consideration the main body of the recycle system, module dimensions and positioning on the vehicle, the cooling fins were dimensioned using the following formulas.

Number of fins (N_f)

Number of canals (N_k)

$$N_k = N_f - 1$$

Width of fins(t_k)

Distance between side surfaces of fins (P_f)

$$P_f = \frac{(W_g - t_f)}{N_f}$$

Distance between fins (S_f)

$$S_f = P_f - t_f$$

Circumference of fluid contact surface(P_{wet})

$$P_{wet} = 2L_f + 2S_f$$

Hydraulic diameter (D_h)

$$D_h = \frac{4L_f S_f}{P_{wet}}$$

Flow input area (A_g)

$$A_g = S_f L_f N_{ch}$$

Original flip height ($L_{k,öz}$)

$$L_{k,öz} = L_f + \frac{T_f}{2}$$

1 Flip circumference (P_k)

$$P_k = 2t_f + 2L_z$$

1 Flip area (A_k)

$$A_k = t_f L_z$$

Total flip surface area (A_t)

$$A_t = 2N_{ch} L_{k,öz} L_z$$

Net surface area (A_{net})

$$A_{net} = A_{mod\,,t} - (A_k N_f)$$

Total effective surface area($A_{t,e}$)

$$A_{t,e} = A_t + A_{net}$$

Reynolds number (Re)

$$Re = \frac{(4\, m_a)}{(\mu\, P_{wet}\, N_{ch})}$$

(m_a=0,085 kg/s, μ_a=1,78 10^{-5} N s/m^2)

Nusselt number (Nu)

$$Nu = \left(0{,}664\, Re^{1/2}\right)(\mathrm{Pr})^{1/3}$$

(AirPrnumber = 0,7309)

Convective transfer coefficient (h)

$$h = \frac{Nu\, \kappa}{D_h}$$

$$m = \left[\frac{h\, P_{face}}{K_{fin}\, A_c}\right]^{1/2}$$

(For aluminium flipsK_{fin} = 200 W/m^2K)

Fin output(η_{fin})

$$\eta_{fin} = \frac{[\tanh(m\, Lf_{char})]}{(m\, Lf_{char})}$$

Total fin output(η_o)

$$\eta_o = 1 - \left[\frac{A_{f,surf}}{A_{tot,surf}}(1-\eta_{fin})\right]$$

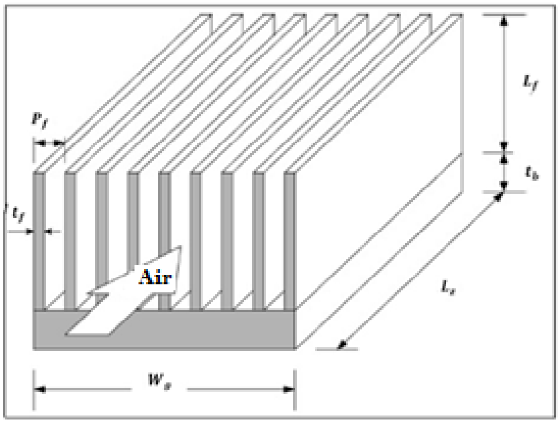

Figure 1.1The designed Al cooler

II. MATERIAL & METHOD

A. *Experimental Setup& Equipment*

Figure 2 shows the experimental setup. A "U" type heater is used to adjust the hot side temperature of TEG. The ET2011 type selectable output PID temperature controller was used to fix the temperature of the hot side. A variable speed cooling fan was used to adjust the temperature of the cold side. The front and back of the system were insulated to reduce heat losses. ELİMKO E-TC15-1K1 type thermocouple temperature gauges were used to measure the temperature of the hot and cold sides. The temperature gauges were placed in the channels between the modules and the aluminium cooler on the cold side and in the centre of the system with the heater on the hot side. The measured temperature values were transferred to the measuring computer through ELIMKO E680 scanner. Measurements were made after constant temperature conditions were obtained at all measuring points. Aluminium cooling fins and TEGs were connected with clamping clamps on the body of the system. CHROMA 6310A DC electronic load was used to measure and record the open circuit voltage, loaded voltage, current and power values and to change the load resistance.

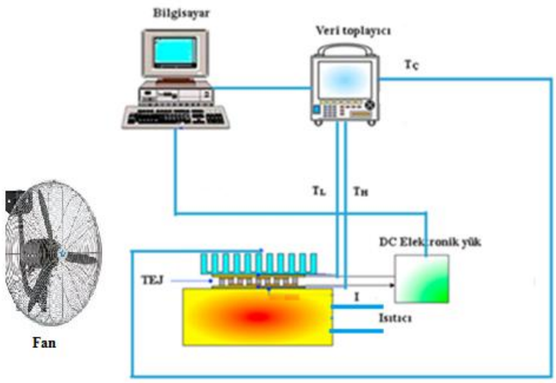

Figure 2.1Experimental setup

B. *TEG*

The main body of the waste heat recycle system was made of aluminium profile (50x50x1 mm). Table 1 shows the technical specifications of the thermoelectric module (TG 12-8) used. When heat energy is converted to electrical energy, as well as electrical energy to cooling energy ,efficiency depends on the electrical and thermal properties of the semiconductor thermo elements.

Table 1.Technical specifications of the thermoelectric module [12]

Thermoelectric generator	
Type number	TG-12-8-01L
Lenght x width x height (mm)	44 x 40 x 3.6
Hot side temperature (°C)	230
Cold side temperature (°C)	50
Thermal resistance (°C/W)	1.13
Load resistance for optimum η	3.46
Optimum efficiency (%)	4.97

C. *Test Procedure*

Waste heat recycle tests were performed by measuring voltage and current values for three different ΔT (ΔT= 20 °C, ΔT= 30 °C, ΔT= 40 °C) depending on the load resistance at the system constant internal temperature (T_h= 250 °C). Contribution of the 2 cooling profiles that were designed and manufactured to system efficiency was compared. $T_h$temperature was set at 250 °C considering the maximum working temperature of TEG. The data obtained in all test procedures were determined by taking the average of the 5 measurements made after the stable conditions were established.

D. Cooling Profiles

The cooler profiles used in the cold zone of the waste heat recycle system have different aluminium alloys and dimensions. The surfaces touching the TEG modules were very precisely machined and the profiles were connected to the main body with tightening clamps in accordance with the recommended tightening torques of the modules. The specifications of the cooling profiles used are shown in Table 2.

Table 2.Technical specifications of heat exchanger

Profile	Material	Thermal Conductivity (W/mC)	Density (kg/m^{3})	Dimensions (mm)	Area (mm^{2})
A	Al6061 t5	167	2710	50x25x200	770
B	AlCuMg 2024	143	2800	50x70x200	1680 ^{2}

III. FINDINGS & EVALUATION

Figure 2 shows the voltage change depending on different load resistances at constant thermal conditions (T_h= 250 °C, ΔT= 20 °C). With the increase in the load resistance, the voltage obtained for each load resistance also increased. The highest voltage value was obtained at R_L= 55Ω load resistance as 10.27 V for profile "A" and 8.92 V for profile "B".

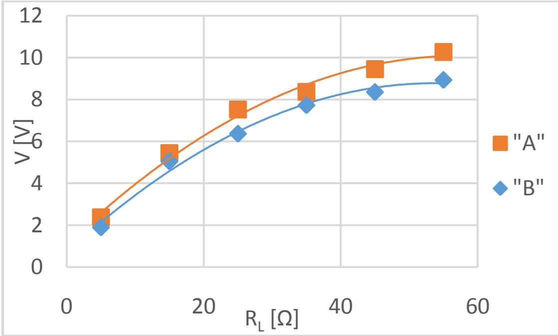

Figure 2. Voltage change depending on load resistance change at constant thermal conditions

Figure 3 shows the current change depending on different load resistances at constant thermal conditions (T_h= 250 °C, ΔT= 20 °C). With the increase in the load resistance, the current value obtained for each load resistance decreased. The highest current value was obtained at R_L= 5Ω load resistance as 0.46 A for profile "B" and 0.32 A for profile "A".

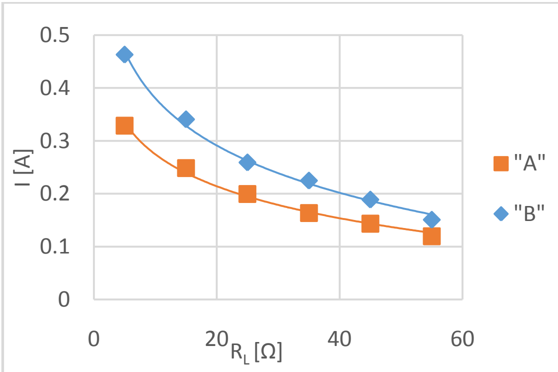

Figure 3. Current change depending on load resistance change at constant thermal conditions

Figure 4 shows the voltage change depending on the load resistance at different thermal conditions for profile "A". With the increase in the load resistance, the voltage value obtained for each load resistance increased. In addition, the increase in ΔT in constant load resistances also increased the voltage value obtained. The highest voltage was measured at T_h= 250 °C, ΔT= 40 °C temperature difference as V= 11.10 V.

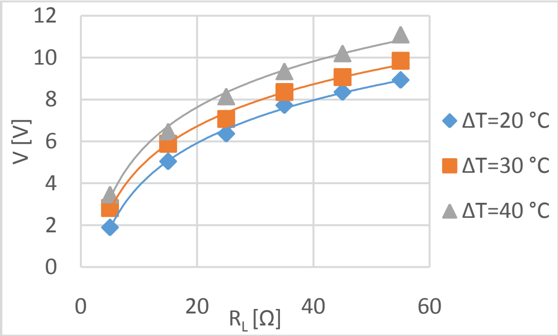

Figure 4. Voltage change depending on load resistance(T_h=250°C and profil"A")

Figure 5 shows the voltage change depending on the load resistance at different thermal conditions for profile "B". With the increase in the load resistance, the voltage value obtained for each load resistance increased. In addition, the increase in ΔT in constant load resistances also increased the voltage value obtained. The highest voltage was measured atT_h= 250 °C, ΔT = 40 °C temperature difference as V= 12.5 V.

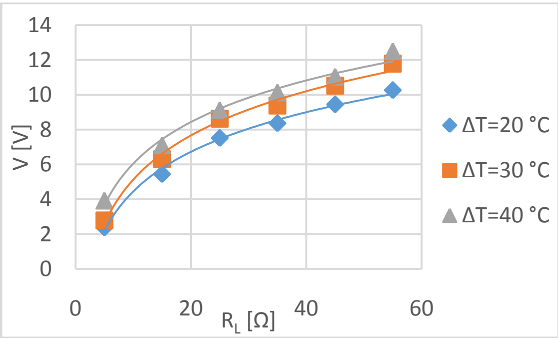

Figure 5. Voltage change depending on load resistance (T_h=250°C and profil "B")

IV. RESULTS

In both designed cooling profiles, the voltage obtained for each load resistance increased with the increase in the load resistance in the constant thermal conditions (T_h= 250 °C, ΔT= 20 °C). With the increase in the load resistance, the current value obtained for each load resistance decreased. In experiments conducted for constant thermal conditions, higher power values than profile "B" were obtained.

The voltage value obtained by increasing the load resistance at different thermal conditions increased. The voltage value obtained with the increase in ΔT at constant load resistance also increased. In experiments conducted for different thermal conditions, higher voltage and power values were obtained from profile "B". The highest voltage for profile "B" was measured atT_h= 250 °C ΔT= 40 °C temperature difference as V= 12.5 V. The length/ area ratio of profile "B" was higher when the ratio of the blade circumference length to the cross-sectional area was taken into consideration. This increased the blade effectiveness. Furthermore, although the thermal conductivity of profile "A" was higher, a greater TEG module cooling was achieved in profile "B", as the blade height was greater and the blade spacingsobstructed the coolant flow less.

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