Converting Waste Heat of Vehicles Exhaust Gases into a Useful Source of Energy

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April 27, 2022

CONVERTING WASTE HEAT OF VEHICLES EXHAUST GASES INTO A USEFUL SOURCE OF ENERGY

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Abstract
Waste heat from car exhaust is 20%-40% of the total heat lost from engine. The aim of this study is to find a new technique that could be used to convert the lost heat from exhaust to a useful source of energy. A useful source of energy can be either heat or power. It has been found that the range of the system efficiency is varied from 30%-37%, which depends on surface temperature that is in contact with the hot side of the thermoelectric generators. Furthermore, the minimum power generated by the thermoelectric generators is equal to 21 Watt.

Keywords: *Heat Recovery, Exhaust Gases; Thermoelectric; Heat -to-Power; Internal Combustion Engines*

1. INTRODUCTION
Due to the increase in energy prices, it becomes more economically profitable to recover and reuse the waste heat that exists in many industrial applications. In automobile sector, only 30 to 40% of the total energy produced in the vehicle's engine is converted to a useful energy and the rest is lost to the environment in the form of exhaust heat (20% - 40%), coolant and lubrication (10%-35%), friction and pumping (2%-10%) and brake power (20% - 40%) (Rajoo et al., 2014; Gao et al., 2019). Waste heat recovery (WHR) is the use of thermal energy that would be wasted to perform a useful function. In many situations, WHR eliminates or decreases the requirement for extra fuel energy input that would be needed to achieve the system functionality. There are two concepts where the heat can be recovered, by either absorbing the heat and converting it to a source of heat or by directly converting the heat into power. These techniques can increase the efficiency of the engine and reduce the consumption of fuel (Chatzopoulou and, Markides, 2018). Generally speaking, WHR will help in increasing the efficiency of the engine, reducing fuel consumption, decreasing global warming, using it for heating and cooling applications, and a lot of other useful applications. In many situations, the purpose of WHR is to produce more work. Higher-quality heat sources enable more waste heat to be turned to work. The "quality" of a specific heat source for the purpose of WHR is strongly affected by its temperature. The higher the temperature of the medium, the greater its entropy, allowing a greater proportion of the heat to be transferred to productive work (Pradhan et al., 2015). In this study, the focus was on what has been achieved during the period (2009-2021). Looking at studies on the period mentioned will help to develop new ways to recover the wasted heat. Weng et al. (2009) used R600a as a working fluid and hot water as a source of heat for an Organic Rankine Cycle. They found that the maximum efficiency of the tested system is 5.2% and the efficiency is insensitive to the temperature of the heat source but sensitive to evaporating pressure. Bundela, and Chawla (2010) did research on how to use heat exchangers with thermos-oil as working fluid. The heat exchanger uses the thermal oil to evaporate the organic fluid which will, in turn, drive a turbine. They found the system will yield a high amount of power. After that, Seher et al. (2012) studied the expansion process in turbine and piston machines using different working fluids such as water and ethanol. They found that using a piston machine with ethanol or water as working fluid and a turbine with ethanol as working fluid is the most favorable solution. Dominguez et al. (2013) conducted analysis on using Rankine cycle for recovering the vehicle exhaust waste heat. They used water, R123, and R245f as working fluids. They found the effectiveness of the organic fluids (R123 & R245f) was more than water. Later on, Mager and Bhosal (2015) used different nanofluids like BN/H20 with two streams of air hot and cold streams. They concluded that the maximum effectiveness was 0.28 by using BH/H20, where the effectiveness of normal working fluids was 0.16. Akbarzadeh et al. (2017) found that the efficiency of the engine increased by using the combination of the thermoelectric generator (TEG) and heat pipes as a new heat recovery technique. Karana

and Sahoo (2018), found that the output power of TEG increases by 11.38% and 9.86% for MgO and ZnO nanofluids respectively, compared to EG-W (type of working fluid). After that, Wahile et al. (2020) used PCM to store heat and generate steam later on, they found at an engine load of 11 kg, it takes 90 minutes to charge the PCM. During the charging procedure, the PCM saved 5.5 % energy from the exhaust. PCM takes 20 minutes and uses just 1.6 percent of the energy in the water to generate steam, with the remaining 3.6 percent lost to the environment. Despite such huge efforts that have been done to recover the exhaust gases water heat the majority of them is using on heat-to-heat converting concept and the achieved results still required to be enhanced by developing a new het recovery system

1.1 The Statistical Information in Oman

From the statistical information of vehicles in Oman between August 2020 and August 2021, an increasing about 0.26-1.14% has been recoded in registered vehicles in Oman. This is reflected to increasing of vehicles exhaust energy losses by 3.208 GW.

Table 1: The amount of heat loss from exhaust vehicles in Oman

Engine capacity	∆Cars number = August 2021 - August 2020	Percentage of increasing or decreasing	Percentage* exhaust heat loss energy	Total ∆ of exhaust heat loss energy
less than 1500	-3764	-3.165%	-3.165%*7.72 GW	-0.244 GW
1500-3000	2162	0.262%	0.262%*105 GW	0.275 GW
3001-4500	1491	0.426%	0.426%*68.9 GW	0.318 GW
more than 4500	2269	1.14%	1.14%*250.8 GW	2.859 GW
			Total	3.208 GW

According to the National Statistics Center in Oman (Information, N. C. 2021), 1.5 - 3 liter capacity engines are the most often used automobiles in Oman, around 54 % (828,501 cars) of all cars in the country. Automobiles with engines ranging from 3 - 4.5 liters are the next category (22.7%). The total heat loss from 1.5 - 3 liter and 3 - 4.5 liter size engines are around 105 GJ/s, and 68.9 GJ/S respectively, which is a very large quantity.

2. METHODOLOGY

The aim of the study is to design a waste heat recovery system for car exhaust that will recover the waste heat and convert it into a useful source of energy. There are many properties related to the design of the system, these properties are gathered from customers and then converted to an engineering specification. After determining the properties, the constraints of the system are set:

- Economic: Affordable cost of the project must be within the limited budget (200 OMR).
- Environmental: Be environmentally friendly by reducing the heat loss from the exhaust.
- Legality: Use appropriate standards and codes through designing.
- Health and safety: Understand any safety aspects, safety standards, and legislation covering the product.
- Sustainability: The system has to be reliable and durable. In addition, the parts of the system should have the same life span.
- Physical: The size and weight of the device must not affect the performance of the car.

After that, five concepts (as shown in Figure 1) have been generated according to all information, properties, and limits defined previously. Concept 1 is about using the heat from the exhaust and converting it into power used for cooling by using thermoelectric generators. Concept 2 is about using the heat from the exhaust and use it to store energy in a battery by using thermoelectric generators and phase change material. Concept 3 is to convert the heat of the exhaust gases into useful heat using piezoelectric generators and phase change material. Concept 4 is to convert the heat of the exhaust gases into electric power and store it by using nanofluid and thermoelectric generators. Concept 5 which about using the heat from the exhaust and use it for heating water by using heating pipes. The evaluation of concepts starts with Absolute criteria and Go/No go screening, which will determine if the concept will be further evaluated, or it will be eliminated. Concepts 3 and 5 were removed because of their size and complexity. After that, Absolute scoring method is used for the remaining concepts. Finally, concept 1 was selected because it got the highest weight.

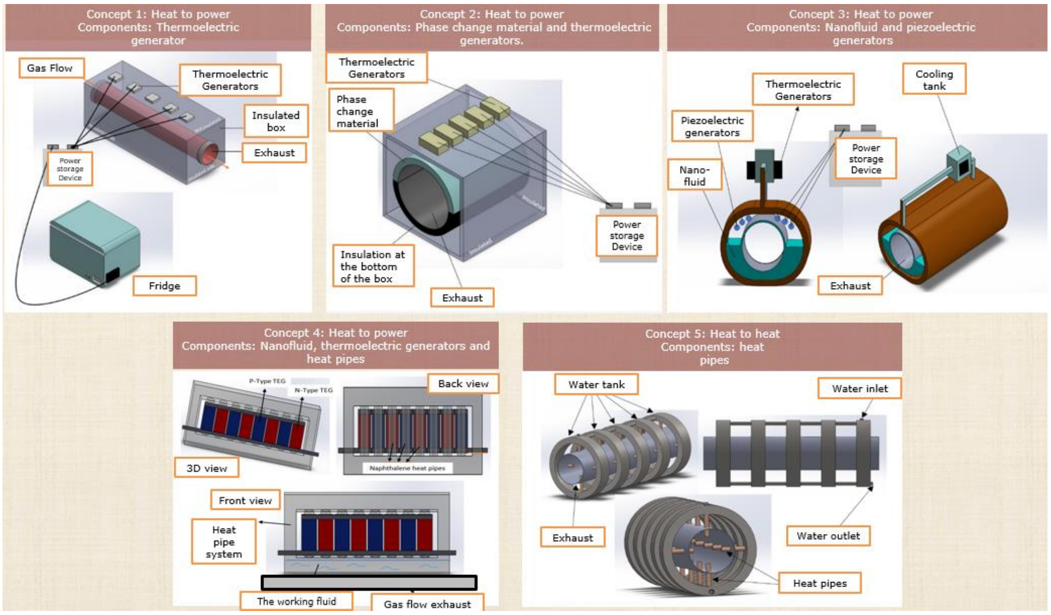

Figure 1. Generated design concept.

3. RESULT ANALYSIS AND DISCUSSION

The concept chosen is Concept 1, which will use heat for cooling. The energy is converted from the outer cover of the exhaust pipe to a voltage by using a thermoelectric generator, that voltage will be supplied to another thermoelectric generator (thermoelectric generator set) used for cooling a space. An overview figure of the system is shown in Figure 2.

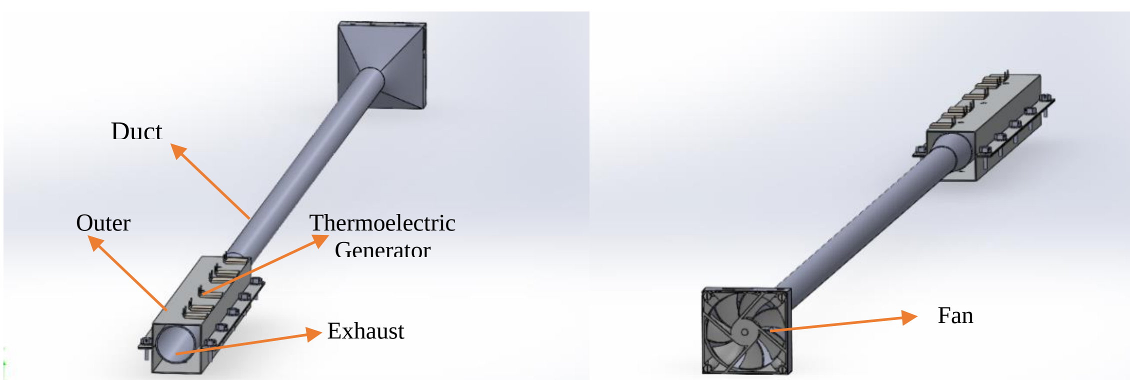

Figure 2. Waste heat recovery system

All the information related to the study are ready and the theoretical calculations of the results were done. These values are obtained by measuring the temperature of the exhaust gas in different speed range (20 km/h – 120 km/h). The type of engine used is 2.0-liter, four cylinders engine. From the data gathered, it has been found that relationship is linear as shown in Figure 3, as the car velocity increases the inlet temperature increases. The equation is obtained using the chart, the inlet temperature can be found at any car velocity.
And the relation is shown in the following chart:

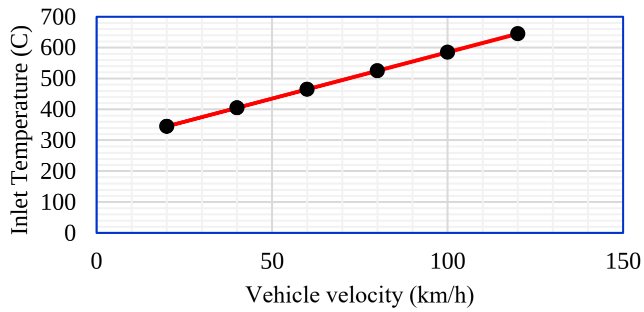

Figure 3. Inlet temperature as a function of vehicle speed

The last parameter is the voltage generated by the thermoelectric generators at different surface temperature. There are different types of TEG available in the market, however our project will be done at high temperature, so a high-quality thermoelectric generator must be selected which can sustain a temperature of more than 350℃, in order to provide a temperature close to the real situation in the exhaust car. During the research in the local and global markets it is found that there is a company in Canada buy a high-quality TEG for high temperature applications. In addition, the company have a TEG which can work at more than 600 ℃ which meet our requirement; however, it is very expansive compared to our budget. Because of that the team members decided to select a lower TEG quality (Module: TEG1-1263-4.3) which can work at a temperature equal to 320℃. The temperature values of the hot and cold side of TEG are approximated to be equal to 250 ℃, 30 ℃ respectively. The next relation is the heat loss and the velocity of the car, the relation is shown in Figure 4. The heat loss was calculated using equation 1.

$$Q = \frac{Ts\ exhaust - T\infty}{R1 + R2} \qquad (1)$$

Where the Ts is the surface temperature of the exhaust, $T\infty$ is the ambient temperature, which approximately equal to 30 Celsius. R1 is the conduction thermal resistance of the air inside the outer cover, and R2 is the convection thermal resistance between the outer cover and the air. The graph shows a proportional relationship between the total heat loss from the exhaust and the car velocity which will affect the mass flow rate inside the exhaust. After that, the relation between the outlet temperature and the velocity of the car is obtained as shown in Figure 5. The car velocity will affect the inlet temperature, and then the outlet temperature will be affected by the inlet temperature.

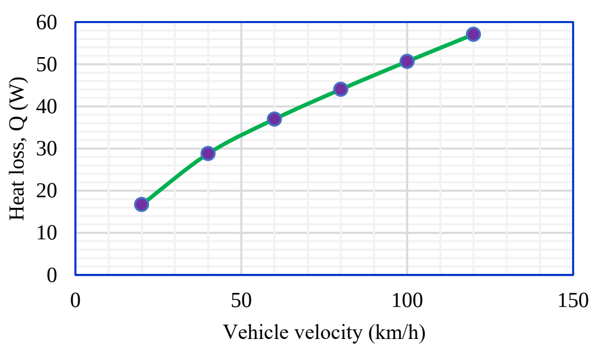

Figure 4. Heat loss as a function of vehicle speed

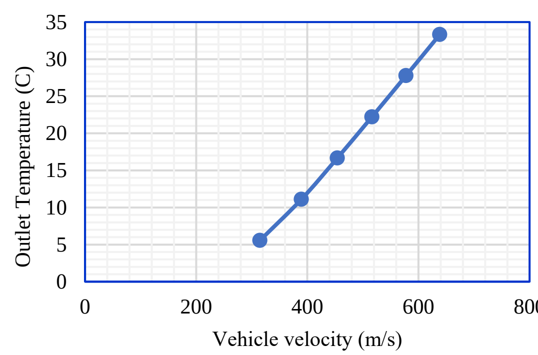

Figure 5. Outlet temperature vs. vehicle speed

The next relation is between surface temperature and car velocity as shown in Figure 6. The heat loss will change by changing the inlet temperature, so the outer cover surface temperature will change and increase as the car velocity increases. Furthermore, the surface temperature and output voltage relationship are shown in Figure 7. The total voltage calculated is based on equation 2.

$$V = 0.0215Ts - 0.575 \qquad (2)$$

Where Ts is the outer cover temperature. This equation is found by the data sheet of the thermoelectric generator, where the curve is assumed to be linear. In addition, the output voltage from the thermoelectric generator and the car exhaust heat loss is related together as shown in Figure 8. As can be seen in the figure the output voltage is directly proportional to the heat loss. The relation between surface temperature and Carnot efficiency is shown in Figure 9. In order to check the system performance, Carnot efficiency has been calculated by the equation 3.

$$\eta_{Carnot} = 1 - \frac{T\infty}{T_s} \qquad (3)$$

Where the $T\infty$ and Ts are ambient and surface temperature respectively. The range of the efficiency is between 40% and 61% as shown in Figure 12, where it is change directly with the surface temperature.

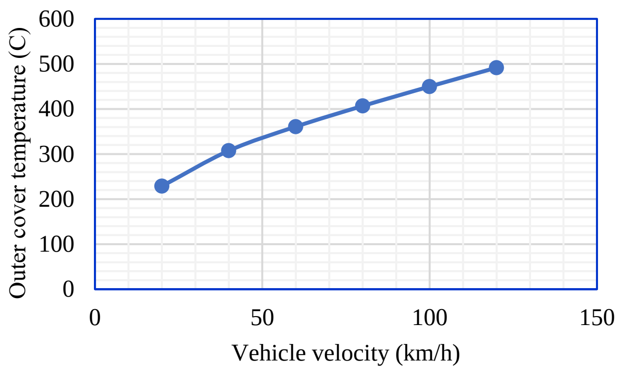

Figure 6. Outer cover temperature as a function of vehicle speed

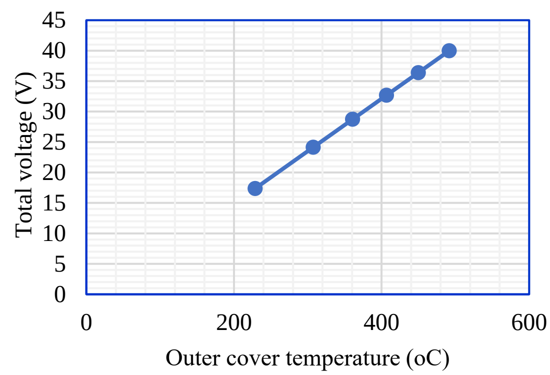

Figure 7. Total voltage as a function of outer cover temperature

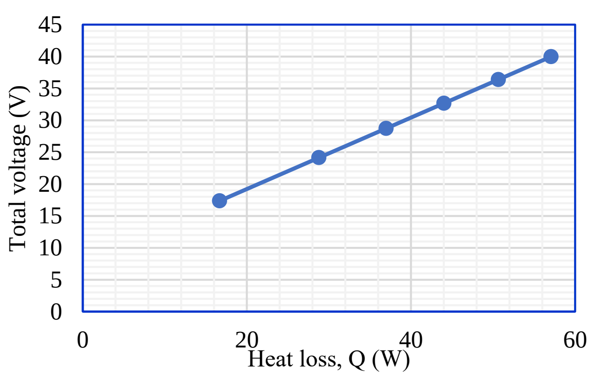

Figure 8. Total voltage as a function of heat loss

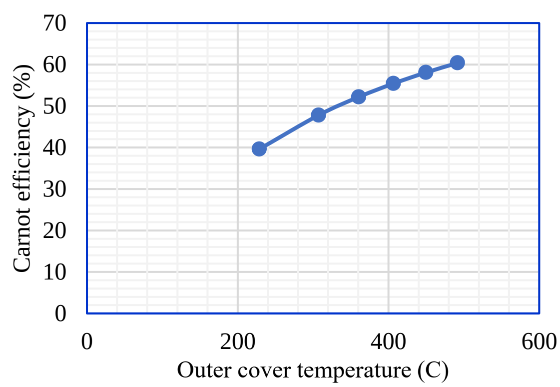

Figure 1. Carnot efficiency as a function of outer cover temperature

Finally, the relation between system efficiency and Carnot efficiency is shown in Figure 10. The system efficiency is lower than the Carnot efficiency, so the results are accepted. The system efficiency is calculated by equation 4.

$$\eta_{Sys} = \frac{Q_{loss}}{W_{TEG-total}} * 100 \qquad (4)$$

Where $W_{TEG} - total$ of the 6 TEGs, where three are connected in parallel and the other three connected in series.

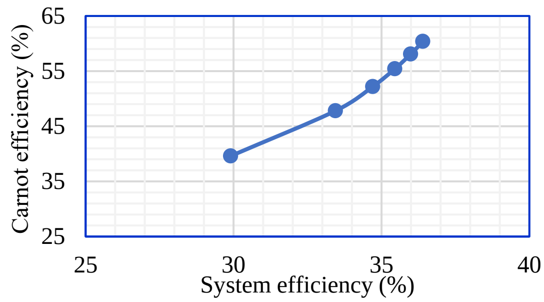

Figure 2. Carnot efficiency as a function of system efficiency

4. CONCLUSIONS

A waste heat recovery system was developed where the heat of exhaust gases converted to power using thermoelectric generators. The dissipated heat from the exhausted was found to have a linear relationship with vehicle velocity and reached to 58 W at 120 km/h. The obtained output voltage reached to 40 Volt with a system efficiency of 37% A useful source of energy can be either heat or power. It has been found that the range of the system efficiency is varied from 30%-37%, which depends on surface temperature that is in contact with the hot side of the thermoelectric generators. Furthermore, the minimum power generated by the thermoelectric generators is equal to 21 Watt.

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