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Electricity generation from an exhaust heat recovery system utilising thermoelectric cells and heat pipes

B. Orr*, B. Singh, L. Tan, A. Akbarzadeh

Energy Conservation and Renewable Energy (Energy CARE) Group, School of Aerospace, Mechanical and Manufacturing Engineering (SAMME), RMIT University, Bundoora East Campus, 3083 Bundoora, Australia

HIGHLIGHTS

- Car exhaust heat recovery design.
- Unique design that utilises heat pipes and thermoelectric cells.
- System is solid state and passive.
- The electrical power produced was 6.03 W.
- The resultant efficiency of the system was 1.43%.

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ABSTRACT

The internal combustion engine used in majority of cars at the present time do not use their fuel input very efficiently. A majority of this energy is dissipated as heat in the exhaust. The related problems of global warming and dwindling fossil fuel supplies has led to improving the efficiency of the internal combustion engine being a priority. One method to improve the efficiency is to develop methods to utilise heat in car exhausts that is usually wasted. Two promising technologies that were found to be useful for this purpose were thermoelectric cells (TECs) and heat pipes. Therefore this project involved making a bench type, proof of concept model of power production by thermoelectric cells using heat pipes and hot engine exhaust gases. 8 cells were used and managed to produce 6.03 W when charging the battery. The system operated with a heat to electricity conversion efficiency of 1.43%. The discrepancy between the actual efficiency and the predicted efficiency of 2.31% is most likely due to the cells not operating at their optimum voltage. The predicted efficiency is approximately 1/9 of the Carnot efficiency and the actual efficiency is approximately 1/15 of the Carnot efficiency.

1. Introduction

The automobile industry has been identified as one of the target industries for the reduction of greenhouse gas (GHG) emissions therefore much research has been undertaken in this area. Despite this intensive research, there have been no clear viable alternatives to the fossil fuelled internal combustion engines (ICE). As progress has been slow in that respect, research must be undertaken to improve the current ICEs efficiency to preserve current fossil fuel supplies until a viable alternate presents itself. Current ICEs are approximately 25% efficient (Fig. 1) under typical driving conditions (i.e.: European driving cycle). Therefore there is lots of room for improvement. Most of the losses for ICEs are heat losses. Therefore this is one area to be targeted. Most of the heat losses can't be prevented therefore methods must be developed to utilise this heat. A lot of this heat is of a lower grade and difficult to utilise. The two areas where the heat is easier to utilise are the exhaust gases and the engine coolant. Engine coolant can only reach a maximum of approximately 90 °C [1]. This is a lower grade of heat than exhaust gases that can reach maximum temperatures of over 400 °C. Approximately 40% of the energy used is wasted in the exhaust gases as shown in Fig. 1. Therefore it is most viable to utilise the exhaust gas heat. This paper identifies TECs and heat pipes for use in an exhaust heat recovery system.

TECs make use of what is known as the Seebeck effect. When one side of the cell is heated and the other side cooled, a voltage is generated. The voltage generation means there are applications for

* Corresponding author.
E-mail addresses: bradley.g.orr@gmail.com, s3236808@student.rmit.edu.au (B. Orr).

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Nomenclature

I	electric current [A]
I_{SC}	cell short circuit electric current [A]
P	electrical power of the system [W]
P_{Carnot}	potential power of system at Carnot efficiency [W]
$P_{predicted}$	power of the system at predicted efficiency [W]
$P_{TEC\ Carnot}$	potential power of individual TEC at Carnot efficiency [W]
$P_{TEC\ predicted}$	power of individual TEC at predicted efficiency [W]
$\dot{Q}$	rate of heat transfer [W]
$\dot{Q}_{in}$	Rate of heat input [W]
R	thermal resistance [°C/W]
T	temperature [°K]
ΔT	temperature difference [°C]
T_c	heat engine minimum operating temperature [°K]
T_h	heat engine maximum operating temperature [°K]
V	voltage [V]
V_{OC}	cell open circuit voltage [V]
ZT	TEC figure of merit

Greek symbols

η	heat to electricity conversion efficiency of the system [%]
η_{Carnot}	Carnot efficiency of the system [%]
$\eta_{predicted}$	predicted efficiency of the system [%]
$\eta_{TEC\ Carnot}$	Carnot efficiency of individual TEC [%]
$\eta_{TEC\ predicted}$	predicted efficiency of individual TEC [%]

these cells to generate electricity where temperature differences are present. This makes them heat engines much like ICEs. The advantages they have over mechanical heat engines are that they are silent, very small, completely scalable and durable. Their key advantage is that they have no moving parts and no chemical reactions therefore there is little maintenance required due to wear and corrosion. Their efficiency is typically 5% [3] compared to about 25% for ICEs but they can generate power from any temperature difference unlike ICEs. As with all heat engines, their efficiency is limited by the Carnot efficiency so the higher the temperature difference, the more efficient they will be. Heat engines have rejected heat which is why one side needs to be cooled.

A heat pipe is a metallic pipe that is sealed at both ends and is partially filled with a fluid at vacuum pressure. Heat pipes are very good heat conductors therefore they are used to transfer heat relatively long distances quickly and efficiently. Their thermal conductivity can be magnitudes higher than copper. A typical use of a heat pipe would be in a laptop computer. In laptops, they are used to transfer heat from the CPU somewhere in the middle of the motherboard to a heat sink on the edge of the motherboard exposed to ambient air. A heat pipe is a completely passive heat transfer device. No fans or moving parts are needed.

2. Current state of the art

Large multinational car companies like BMW [4], Ford [5] and Honda [6] have demonstrated their interest in exhaust heat recovery, developing systems that make use of TECs. Their method was to connect the circular exhaust to an expansion chamber using a flange. One side of the cells was placed on the faces of the expansion chamber and the other side of the cells was cooled by a

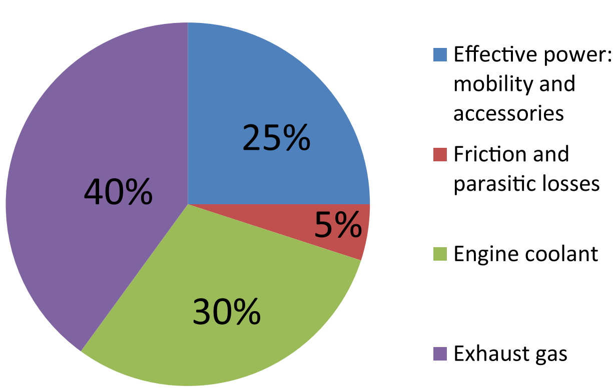

Fig. 1. Energy distribution of a typical ICE [2].

liquid coolant. The coolant could be from the main car radiator or an independent radiator. This technology has not yet been installed in present production cars and is still in the concept stages. There are many similar designs with the differences being the shape of the expansion chamber (i.e.: hexagonal) and the method of cooling (i.e.: air cooled).

A waste heat recovery system has been developed to replace a traditional car radiator [2,7]. The aim was to replace the radiator without introducing an extra moving component. Only existing moving components like the water pump and fan were used. The use of heat pipes and TEGs allowed for heat transfer and power production without introducing extra moving parts. This system makes use of the waste heat in the coolant rather than the exhaust gases. The system consisted of 72 TEGs of 40 mm by 40 mm size. 128 small diameter heat pipes were used. During idle conditions the hot side was approximate 90 °C and the cold side was approximately 70 °C. During these conditions 28 W were produced. When run in the driving mode of 80 km/h, the hot side was approximately 90 °C and the cold side was approximately 45 °C. During these conditions 75 W were produced.

There are two examples of exhaust heat recovery using both thermoelectric cells and heat pipes. For the first example [8], the exhaust gases flow through an exhaust pipe with heat pipes protruding through. The heat pipes absorb some of the heat and spread it through the aluminium block they are inserted into. The hot side of the thermoelectric cells are placed on the surface of the aluminium block. The rejected heat from the cells is removed by a water cooled heat sink placed on the other side of the cells. This system generated a maximum of 350 W using 112 40 mm × 40 mm thermoelectric cells.

The second example [9–11] works in a similar way by using the heat pipe to extract the heat from the exhaust gases to the hot side of the thermoelectric cells and using a water heat sink to cool the other side of the cells. In this case a variable conductance heat pipe (VCHP) is used instead of a standard heat pipe. A VCHP operates in the same way as a standard heat pipe but can maintain a steady operating temperature. A VCHP contains non condensable gases inside. With increasing heat load, these gases are pushed up the heat pipe and into the expansion tank. This increases the length of the condensing section. Therefore with an increasing heat load, the operating temperature does not change because of the increasing condenser length removing more heat. Keeping a steady heat pipe operating temperature despite varying heat loads is useful when using thermoelectric cells because the cells can fail when operating over their rated maximum temperature.

A prototype exhaust heat recovery system was implemented into a bus for the purpose of interior heating [12]. The system uses heat pipes to extract the heat from the exhaust gases and transfers