A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes

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A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes

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ABSTRACT

The internal combustion engine (ICE) does not efficiently convert chemical energy into mechanical energy. A majority of this energy is dissipated as heat in the exhaust and coolant. Rather than directly improving the efficiency of the engine, efforts are being made to improve the efficiency of the engine indirectly by using a waste heat recovery system. Two promising technologies that were found to be useful for this purpose were thermoelectric generators (TEGs) and heat pipes. Both TEGs and heat pipes are solid state, passive, silent, scalable and durable. The use of heat pipes can potentially reduce the thermal resistance and pressure losses in the system as well as temperature regulation of the TEGs and increased design flexibility. TEGs do have limitations such as low temperature limits and relatively low efficiency. Heat pipes do have limitations such as maximum rates of heat transfer and temperature limits. When used in conjunction, these technologies have the potential to create a completely solid state and passive waste heat recovery system.

1. Introduction

Before a new car is released to the market, testing is undertaken to ensure it meets the latest emissions regulations. The regulations differ from country to country, but they are always getting more stringent. The CO_2 emissions of a car are proportional to its fuel consumption. Therefore, to meet these tightening regulations, car companies must reduce the fuel consumption of their cars. Current ICEs are on average approximately 25% efficient [1] under typical driving conditions (i.e.: European driving cycle) but can range from 20% to 45% depending on the engine type and operating conditions. The remaining 55%–80% will be wasted as heat in both the coolant and the exhaust gases. A waste heat recovery system has the potential to convert some of this waste heat into electricity and consequently reduce the fuel consumption of the car by reducing the load on the car alternator. Heat pipes and TEGs could be used in conjunction for use in a waste heat recovery system. Their compact size and solid state design make them ideal for automotive applications.

TEGs make use of what is known as the Seebeck effect which is explained in Fig. 1. A TEG is made up of many elements of N type and P type semiconductor materials which are connected electrically in series but thermally in parallel. When one side of the TEG is heated and the other side cooled, a voltage is generated. The voltage generation means there are applications for these TEGs to generate electricity where temperature differences are present. Their efficiency is typically 5% [2] and they can generate power from any temperature difference. Their efficiency is limited by the Carnot efficiency so the higher the temperature difference, the more efficient they will be. A TEG operates at approximately 20% of the Carnot efficiency over a wide temperature range [3]. The thermoelectric figure of merit (ZT) can be used to compare the efficiencies of different TEGs operating at the same temperatures. The higher the ZT, the better the TEG. The ZT of thermoelectric has improved over time but presently the best commercially available TEGs have a ZT of approximately 1 [3].

Compared to other waste heat recovery technologies, the use of TEGs in a waste heat recovery system has many desirable attributes such as silence, small size, scalability and durability. Their key attribute 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 relatively low compared with a Rankine cycle waste heat recovery system [4] but as there are no costs associated with waste heat, efficiency is not the most important factor.

The most popular form of thermoelectric material is Bismuth Telluride. The use of this material in generators is limited because their maximum hot side operating temperature is relatively low. As they are widely used and mass produced, their cost is low compared to other thermoelectric materials. Other materials and techniques have been used to improve the power generation and efficiency of TEGs. The most promising and practical materials to be used for TEGs in

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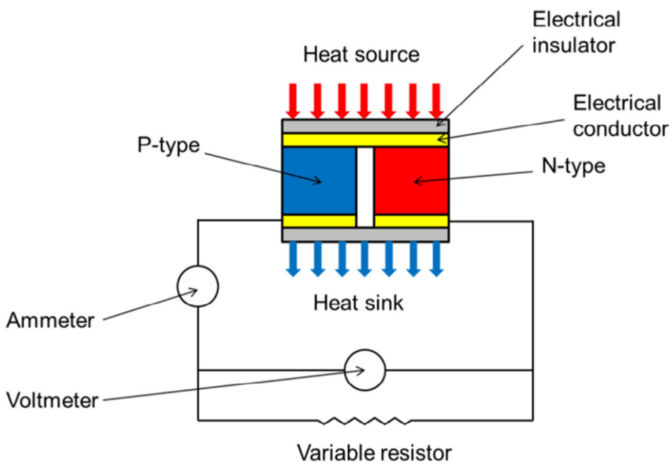

Fig. 1. Seebeck effect.

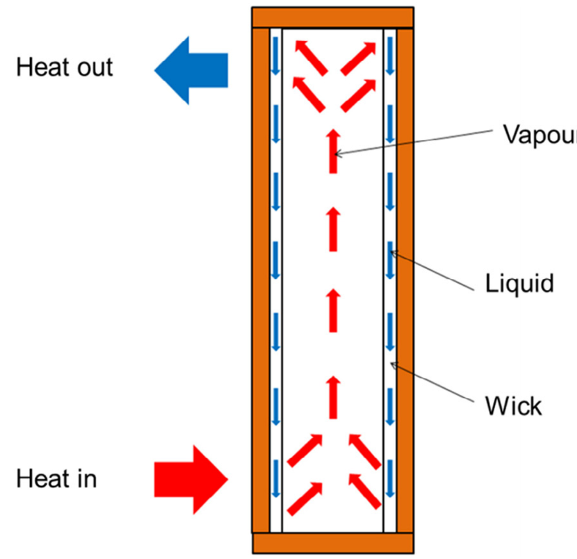

Fig. 2. How a heat pipe works.

exhaust heat recovery systems would be materials rated for a high temperature. This means a larger temperature difference can be present and potentially more power and higher efficiency can be achieved. The use of high temperature TEGs also allows for the simplification of a design because efforts do not need to be made to prevent the TEGs from overheating. Lead telluride and calcium manganese have been used as materials in TEGs due to their ability to handle higher temperatures. Some TEGs have been manufactured with segmented material. A material with a high ZT at higher temperatures is used on the hot side (i.e.: lead telluride) and a material with a high ZT at lower temperatures is used on the cold side (i.e.: bismuth telluride). More power would be produced compared to a TEG made of just the high temperature rated material. Other materials such as skutterudites and other manufacturing techniques such as quantum well structures have been investigated to improve TEG power generation efficiency [5] but they are still very expensive and not commercially available.

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 have a very high effective thermal conductivity therefore they are used to transfer heat relatively long distances with minimal thermal resistance. Their thermal conductivity can be magnitudes higher than copper. A heat pipe is a completely passive heat transfer device. No fans or moving parts are needed. Water is typically used as the working fluid but other fluids can be used for different operating temperatures [6].

Heat pipes consist of an evaporator section, an adiabatic section and a condenser section. As the pressure inside the pipe is nearly at vacuum pressure, the liquid changes phase to vapour at relatively low temperatures. Only saturated liquid and saturated vapour are inside. When heat is applied to the evaporator section, the liquid turns to vapour and travels up to the condenser section. The colder condenser section condenses the vapour back to liquid, consequently removing heat. The liquid then returns to the evaporator in a wick using capillary action. The cycle then repeats itself. This process is explained in Fig. 2.

The use of heat pipes in a waste heat recovery system has a number a benefits and limitations. When fins are used in the gas stream, heat pipes can be used to increase the fin efficiency which consequently reduces the thermal resistance between the TEG and gases. This will allow the TEG surface temperature to be closer to the gas temperature. In some cases, reduction of pressure loss is a higher priority. The higher fin efficiency allows for less fin surface area to be used which consequently reduces pressure losses. Heat pipes can be used to vary TEG temperatures by altering the evaporator and condenser lengths or by using special types of heat pipes such as variable conductance heat pipes. The use of heat pipes allows for more flexible designs as without heat pipes, the location of the TEGs are limited to the exhaust pipe surface.

A limitation of heat pipes is that they have a maximum rate of heat transfer. If the expected rate of heat transfer is extremely high, it may not be practical to have the required quantity and size of heat pipes. Another limitation of heat pipes are their working temperature ranges. If the temperature is too high, the high pressure inside the heat pipe may lead it to rupture. Water heat pipes typically have a working temperature range from room temperature to approximately 300 °C [6] but thick walled heat pipes need to be used to increase the working temperature range of the water heat pipes up to 300 °C. If temperatures above that limit are required, then different working fluids are to be used. Naphthalene has a working temperature range from 250 °C to 450 °C [7] and liquid metals such as potassium and sodium have even higher working temperature ranges. Unfortunately, compared to heat pipes using water, heat pipes using other working fluids are expensive.

2. Automotive waste heat recovery systems using TEGs

Large multinational car companies like BMW [8], Ford [9], Renault [10] and Honda [11] have demonstrated their interest in exhaust heat recovery, developing systems that make use of TEGs. All of their designs are relatively similar. Typically the TEGs are placed on the exhaust pipe surface (shaped as a rectangle, hexagon, etc.) and they are cooled with cold blocks using engine coolant. Examples of a rectangular shaped and hexagonal shaped heat exchanger can be seen in Figs. 3 and 4 respectively [12]. This technology has not yet been installed in present production cars and is still in the concept stages. The BMW system uses a shell and tube heat exchanger. High temperature TEGs are used and the system is rated to produce 750 W from a number of 20 W rated TEGs. The Ford system heat exchanger uses many small parallel channels lined with thermoelectric material for the exhaust gases to pass. Liquid cooling is used in this case. This system is rated to produce a maximum of approximately 400 W with 4.6 kg of thermoelectric material. The Renault system is to be used on a diesel truck engine. It has dimensions of 10 cm × 50 cm × 31 cm. This system uses a counter flow heat exchanger arrangement using liquid cooling. A combination of high temperature TEGs at the high temperature end and low temperature

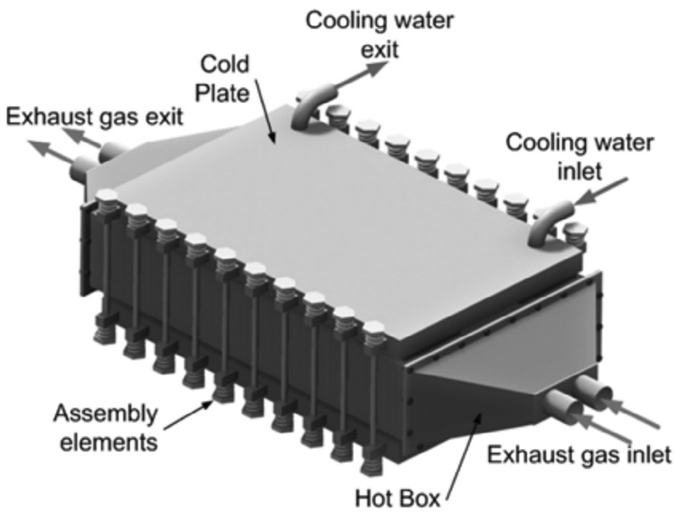

Fig. 3. Rectangular exhaust heat exchanger.

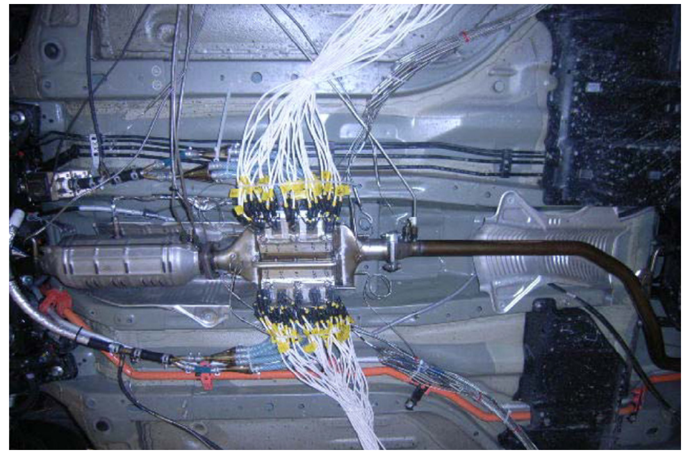

Fig. 5. Honda prototype TEG exhaust heat recovery system.

TEGs at the low temperature end were used. The modelled system is predicted to produce approximately 1 kW. The Honda system used a simple design of a thin flat rectangular box with TEGs placed on the top and bottom surfaces. Liquid cooling was used in this design. The system consisted of 32 30 mm × 30 mm TEGs and produced a maximum of approximately 500 W. The claimed fuel consumption reduction is 3%. An image of the prototype from Honda can be seen in Fig. 5. Alternative heat exchanger designs have been explored such as a design by Dai et al. [13] which used liquid metal exhaust heat exchanger with a solid state electromagnetic pump. The liquid metal transfers the heat from the exhaust gases to the hot side of the TEGs. The liquid metal used was a GaInSn alloy with a melting point of 10.3 °C. A total of 40 50 mm × 50 mm BiTe TEGs were used and the system managed to power a 120 W LED lighting array. Alternative heat exchangers on the cold side of the TEGs have been explored such a design by Hsu et al. [14] which used finned air cooled aluminium heat sinks. This system used 24 BiTe TEGs and generated a maximum of 12.41 W with an average temperature difference of 30 °C.

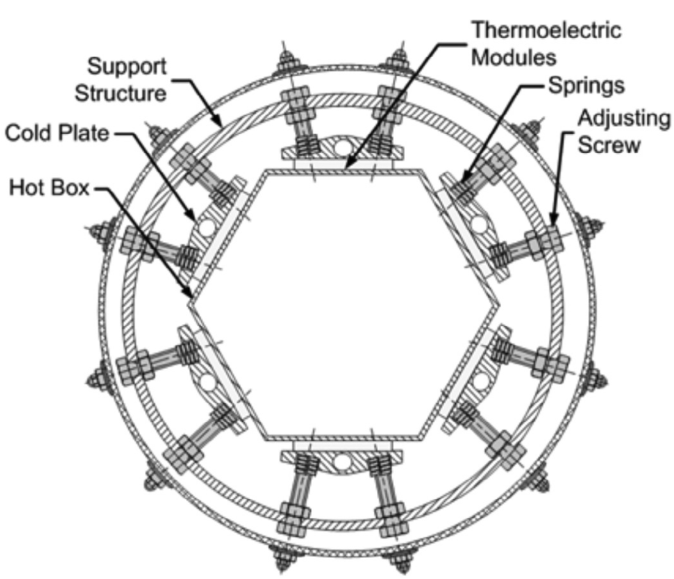

Fig. 4. Hexagonal exhaust heat exchanger.

3. Automotive waste heat recovery systems using TEGs and heat pipes

A waste heat recovery system has been developed by Kim et al. and Baatar et al. to replace a traditional car radiator [1,15]. This system is shown in Fig. 6. 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. 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 approximately 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.

Kim et al. [16] has designed an exhaust heat recovery using both TEGs and heat pipes as demonstrated in Fig. 7. In this system, 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 TEGs are placed on the surface of the aluminium block. The rejected heat from the TEGs is removed by a water cooled heat sink placed on the other side of the TEGs. This system generated a maximum of 350 W using 112 40 mm × 40 mm TEGs.

Goncalves et al., Brito et al. and Martins et al. [17–20] developed a system that works in a similar way by using the heat pipe to extract the heat from the exhaust gases to the hot side of the TEGs and using a water heat sink to cool the other side of the TEGs. In this case a variable conductance heat pipe (VCHP) is used instead

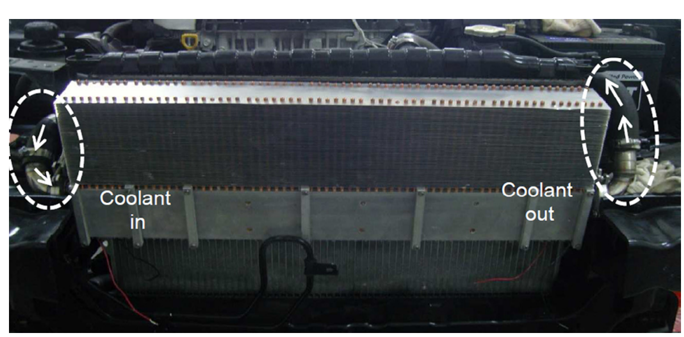

Fig. 6. Combined radiator and TEG waste heat recovery system.

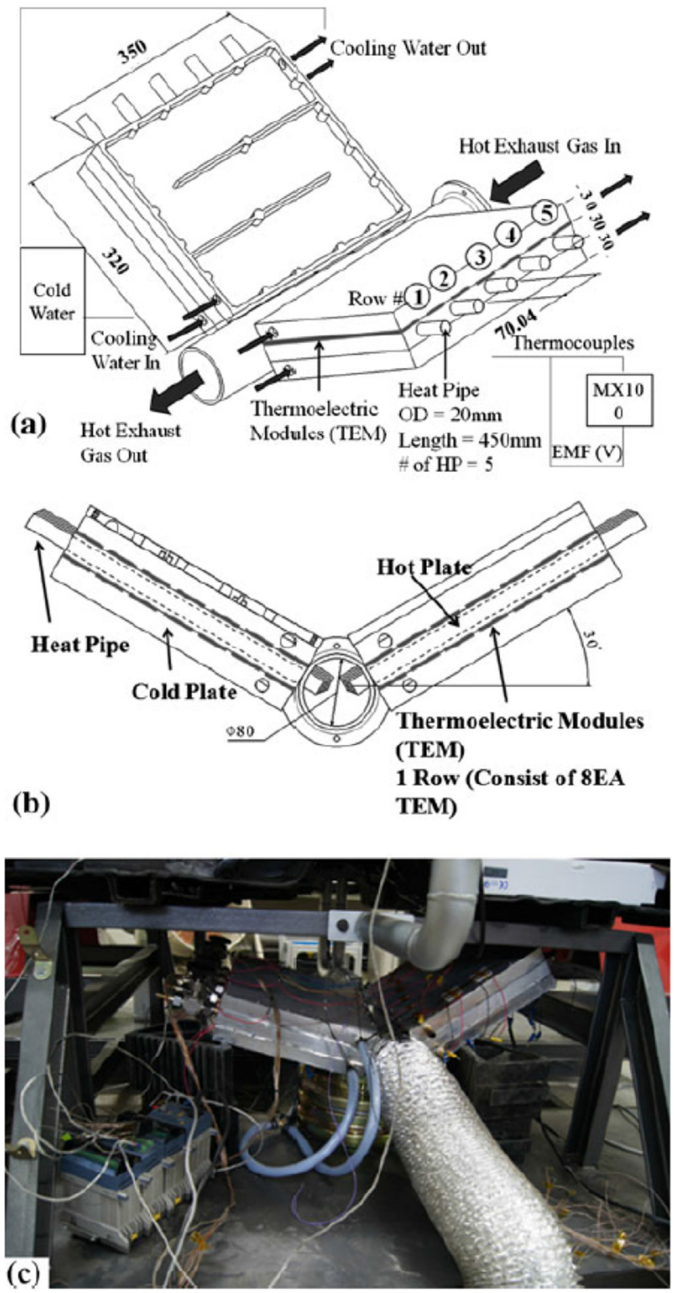

Fig. 7. Exhaust heat recovery system utilising both TEGs and heat pipes.

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 TEGs because they can fail when operating over their rated maximum temperature. The actual system and schematic can be seen in Fig. 8.

Shown in Fig. 9 is a bench type proof of concept exhaust heat recovery system developed by Orr et al. [21]. This system used heat pipes on both sides of the TEG for transferring heat both to and from the TEG. This design demonstrated how the thermal resistance on the hot and cold sides of the TEG can be kept relatively low without

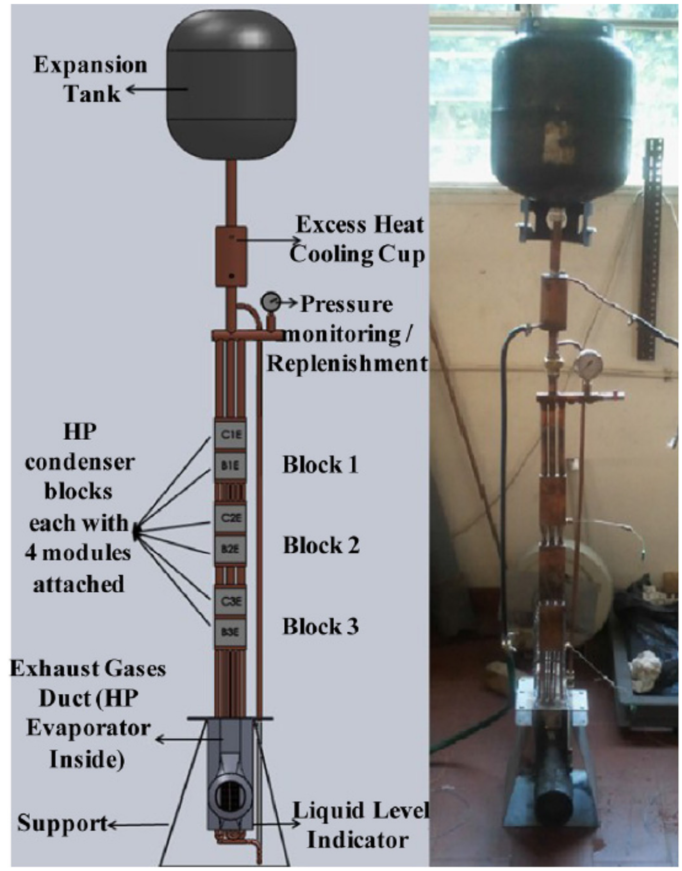

Fig. 8. TEG temperature regulation using a VCHP in an exhaust heat recovery system.

having to introduce moving components. The system is air cooled using a fan to simulate air flow from a car moving at speed. A counter flow heat exchanger arrangement was used to maximise the rate of heat transfer. Exhaust gases were supplied from a small 50 cc gasoline engine. A total of 8 40 mm × 40 mm TEGs were used which generated approximately 6 W of power. A similar design is also demonstrated by Remeli et al. [22] but in this case for industrial waste heat recovery.

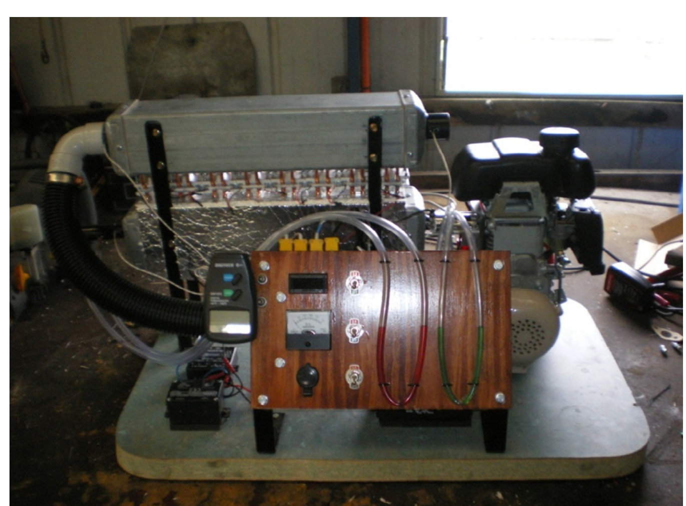

Fig. 9. An exhaust heat recovery system using heat pipes to transfer heat both to and from the TEGs.

Fig. 10. Using a Naphthalene heat pipe preheat exchanger to prevent the TEGs from overheating.

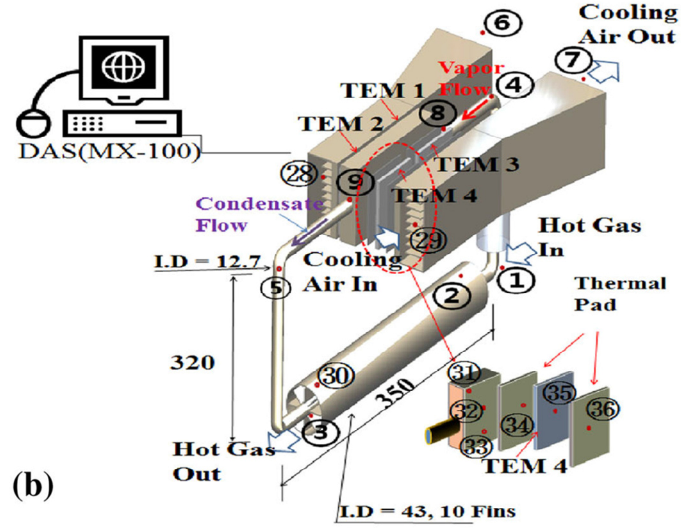

Fig. 11. An exhaust heat recovery system using a loop heat pipe to extract the heat.

Orr et al. [23,24] further developed the design shown in Fig. 9 to be able to handle higher exhaust temperatures. The newer design is shown in Fig. 10. In this case, thick walled copper water heat pipes were used to increase the temperature capability of the heat pipes. Higher temperature rated TEGs and higher temperature rated thermal paste were also used. A naphthalene heat pipe pre heat exchanger was proposed to reduce the exhaust gas temperature and protect the downstream TEGs and copper water heat pipes from overheating. As the naphthalene heat pipes have a working temperature range between 250 °C and 450 °C, when the exhaust gas temperature is low, no heat will be removed but when the exhaust gas temperature is high, heat will be removed. The naphthalene heat pipes work as a temperature regulator of the incoming exhaust gases. When 8 75 mm × 75 mm TEGs are used, the system is predicted to produce 54 W of electricity.

Jang et al. [25] have proposed an alternative exhaust heat recovery design that utilises both TEGs and heat pipes. Rather than using traditional heat pipes, this design makes use of loop thermosiphons. The evaporator section of the loop thermosiphon runs along the length of the exhaust pipe and the condenser section runs along the length of a metallic block for which the TEGs are to be placed. Finned air cooled heat sinks were proposed for cooling of the TEGs. This system can be seen in Fig. 11.

4. Conclusion

Investigations have found that an appropriate way of improving the overall efficiency of the fuel use in a car is to recover some of the wasted heat. Two technologies identified to be of use for waste heat recovery are TEGs and heat pipes. It was found that:

- Both TEGs and heat pipes are solid state, passive, silent, scalable and durable.
- Heat pipes can reduce the thermal resistance between the TEG and gases
- Heat pipes can reduce the pressure losses in the gas stream due to a reduced fin surface area.
- The use of heat pipes allows for more design flexibility because TEG placement is not limited to the exhaust pipe surface.
- Heat pipes can be used for temperature regulation of the TEGs.
- TEGs have limitations such as relatively low efficiency and maximum surface temperatures.
- Heat pipes have limitations such as maximum rates of heat transfer and working temperature ranges.
- A completely passive and solid state exhaust heat recovery system can be developed using both TEGs and heat pipes.

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