

Temperature Controlled Exhaust Heat Thermoelectric Generation

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ABSTRACT

The amount of energy wasted through the exhaust of an Internal Combustion Engine (ICE) vehicle is roughly the same as the mechanical power output of the engine. The high temperature of these gases (up to 1000°C) makes them intrinsically apt for energy recovery. The gains in efficiency for the vehicle could be relevant, even if a small percentage of this waste energy could be regenerated into electric power and used to charge the battery pack of a Hybrid or Extended Range Electric Vehicle, or prevent the actuation of a conventional vehicle's alternator.

This may be achieved by the use of thermodynamic cycles, such as Stirling engines or Organic Rankine Cycles (ORC). However, these systems are difficult to downsize to the power levels typical of light vehicle exhaust systems and are usually bulky. The direct conversion of thermal energy into electricity, using Thermoelectric Generators (TEG) is very attractive in terms of minimal complexity. However, current commercial thermoelectric modules based on Seebeck effect are temperature limited, so they are unable to be in direct contact with the exhaust gases. A way to downgrade the temperature levels without significantly reducing the regeneration potential is to interpose Heat Pipes (HP) between the exhaust gas and the Seebeck modules in a controlled way. This control of maximum permissible temperature at the modules is achieved by regulating the pressure of phase change of the service fluid of the HP. In this way the system will be failsafe against overheating and will be able to operate efficiently under both low and high thermal loads. Such is the case of the range extender unit being developed by the team, which has a low (15kW) and a high (40kW) power mode of operation.

Various designs concepts were evaluated by simulation, design and test. Although efficiencies were still moderate, it was possible to demonstrate the potential of this system for optimizing the output of commercially available temperature limited TEGs.

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1. INTRODUCTION

1.1. Motivation

Lately, a global trend to cut emissions and increase energy efficiency is being pursued by the transportation industry [1] in order to comply with the evermore stringent current and future national and international agreements and policies on GHG emissions, such as the Climate and Energy Package issued by the European Commission [2] and the Corporate Average Fuel Efficiency (CAFE) in the USA [3]. Although a significant effort has been done to date in order to reduce energy waste in Internal Combustion Engines, there is still a big portion, around two thirds of the total energy released by combustion that is wasted through the tailpipe and the engine cooling systems in approximately equal parts [4, 5].

Energy waste may be reduced by the use of strategies that improve energy efficiency such as turbo-charging and over-expansion, but this improvement is still limited. A step further in energy efficiency would be to recycle exhaust heat in some way. Some works have proposed the use of a heat exchanger at the exhaust pipe to recover the heat and redirect it to the system. It can then be used, for instance, to heat up the engine oil more quickly in order to improve energy efficiency during cold starts [6]. The gradual electrification of the vehicle is making the electric recovery of this thermal energy more attractive. This would be especially useful in Hybrid Electric Vehicles (HEV), range extended electric vehicles (EREV) and vehicles with only mild electrification such as those with Start-Stop and related technologies. Even conventional vehicles would benefit from this recovery being able to reduce alternator electricity production power.

Both Organic Rankine Cycle (ORC) turbines [7] and thermoelectric Generators (TEG) based on the Seebeck effect [8, 9, 10] have been tested in heavy duty vehicles for electric exhaust heat recovery during the last decades. Nevertheless, all three have limitations. ORCs have the highest recovery potential but they are still not viable for low duty engines [11], although some effort in low power applications has been made recently [12]. On the other hand, the efficiency of TEG systems has been improving significantly in the last few years due to the application of novel materials technology [13, 14] but currently available systems still display a lower efficiency than ORCs. Nonetheless, for low power applications they currently stand as the only practical option since they are intrinsically scalable [11].

The first tests of thermoelectric generation applied to automotive waste heat recovery started some decades ago with works such as the one made by Neild [15], and other works made with modified cars/engines such as a Porsche 944 [16], a 14 litre Cummins Turbo-diesel engine truck [17] a GM Sierra Pickup Truck [18] and other, more recent works [19, 20, 21, 22]. However, the power recovered was hardly enough to meet the electric demands of the various electrical accessories. Nonetheless, if the recovery potential of the cooling, lubrication and exhaust systems is combined, it should be possible to recover a significantly higher amount of energy [23, 24]. Major OEMs like Honda [25] and BMW are testing this technology. The latter is making plans to commercialize in the near future a car with TEGs generating up to 1kW (currently 200W), with the aim of 5% fuel savings [26].

Works such as [27] point out to the possibility of having an efficiency of heat recovery (to electricity) using advanced thermoelectric generators of 5%, which would translate into an extra 6% (1% from coolant, 5% from exhaust) of available (electric) energy in a hybrid car. Consequently, an engine with 33% efficiency could earn 3% extra mechanical power, translated into 5% in fuel savings.

A major limitation of current commercially available TEGs is that they cannot safely withstand the temperature levels found in typical exhaust systems, which easily exceed 500°C under high loads. This fact enforces the downgrading of the operating temperature of the modules. Of course, this means reducing the energy conversion potential according to the second law of thermodynamics, but for now it is an inevitable limitation that hopefully will be mitigated over time. In fact, the current temperature limitation of TEGs such as those made with Bismuth Telluride alloys (320°C to 350°C limit) has more to do with the frailty of the solderings rather than with the melting point of the alloy itself. For well known fixed operating conditions, it would be possible to thermally dimension a system so as to work at a specified operating temperature, but this passive system would have poor performance below nominal loads and would risk seizure for excessive loads. Some systems had to incorporate gates and actuators in order to by-pass part or all of the exhaust flux in

order to avoid system meltdown. This translates into added cost and complexity.

A solution for passively avoid TEG overheating at high thermal load while simultaneously providing efficient operation even at low loads seems to lie in a system that would be capable of maintaining the desired operating temperature irrespective of the regime by automatically adjusting the heat flux reaching the TEGs. This could be achieved through the use of heat pipes with adjustable boiling temperature, such as the Variable Conductance Heat Pipes (VCHP). One advantage of this system is that it displays a very low thermal resistance. Therefore, taking into account that this application has to be temperature limited, a solution like this one allows maximizing the thermal efficiency for those conditions.

The group started exploring the potential of exhaust energy recovery within the scope of a supermileage contest for hybrid vehicles, with a preliminary assessment of systems with and without heat pipe assist [28]. Another paper detailed some of the results obtained with simplified proof-of-concept installations [29]. A more recent work dealt with the theoretical modelling of a TEG-heat pipe system [30]. The present work is being made in the scope of the development of a Range Extender for an electric vehicle. This particular Range Extender, based on the concept of over-expansion (Miller cycle, in which the authors have expertise [31]), is to be used under two different regimes. The default regime is used for maximizing efficiency and displays a low thermal load (around 15kW). There will also be a regime that engages whenever extra power is needed, producing around 40 kW of mechanical power. A system such as the one described above is needed to allow an efficient electric recovery in both regimes. In the present work results concerning conveniently instrumented TEGs with heat pipe assist are presented in order to assess the potential of heat pipe-based systems for thermoelectric generation of engine waste exhaust heat. A method for safely controlling the maximum temperature achieved by TEGs in exhaust systems is assessed with several proof-of-concept prototypes. As the modules are somewhat expensive and the engine is expected to run at light load for most of the time, the aim of the project is to design the system for these light load conditions, therefore requiring a safety strategy against module overheating.

1.2. Thermoelectric Generators (TEGs)

Thermoelectric generators (TEG) are based on the Seebeck effect. A temperature difference between the junctions of two different materials generates a voltage. Depending on the electrical resistance of these materials, an electric current will flow when the circuit is closed, and electrical power will be available. The overall performance of the TEG, quantified with the figure-of-merit (ZT), depends on three main parameters: Seebeck coefficient (α), electrical resistivity (ρ) and thermal conductivity (λ) at a given temperature (T):

$$ZT = \frac{\alpha^2}{\rho \cdot \lambda} T$$

The efficiency of a TEG module (η) will be dependent on ZT and the temperatures along its surfaces, cold and hot sides, respectively T_C and T_H :

$$\eta = \left(\frac{T_H - T_C}{T_H} \right) \left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}} \right)$$

A candidate for a good thermoelectric material must have a high Seebeck coefficient (a large voltage is generated for a given temperature difference), a small resistivity (a large current could be drawn from the generator) and a small thermal conductivity (the temperature difference between the hot and cold faces of the TEG may be maximized, increasing the efficiency). The ZT can also be calculated at a given temperature T for a thermoelectric module (instead of a single material), considering the voltage generated for each degree of temperature difference V [VK-1], the electrical resistance R_i [Ω] and the thermal conductance K [WK-1]

$$ZT = \frac{V^2}{R_i \cdot K} T$$

The commercially available thermoelectric modules, made of Bismuth Telluride and Antimony Telluride have top efficiency in the range between 0 to 200 °C but ZT decreases for temperature above 200 °C, thus reducing efficiency. Moreover, mechanical stability of these modules often limits operation temperature to a maximum around 250 °C.

The thermoelectric modules produce a voltage (V_O) that is proportional to the temperature difference between the hot and the cold plates of each module:

$$V_O = n\alpha(T_H - T_C)$$

where n is the number of thermoelectric modules. The mean Seebeck coefficient is considered, since the Seebeck coefficient is not constant over the working temperature range. All modules are connected electrically in series, thus the total voltage generated (V_O) and the total internal resistance (R_i) are the sum of the voltage produced by each module and the internal resistance of each module, respectively.

The maximum power output of the modules for a load (P_O) occurs when the load resistance (R_L) equals the sum of internal resistance of the modules (R_i is the electrical resistance of each module and $n \cdot R_i$ is the total resistance, when the modules are connected in series). A mean value is used since the resistance is not constant over the working temperature range.

$$P_O = \frac{(n\alpha(T_H - T_C))^2}{4nR_i}$$

Previous work [30] from the authors demonstrated that these modules could be used for energy generation in automobile applications. TEGs can be electrically modulated as a voltage source (dependent from the temperature at both sides) with an internal electric resistance (R_i). The almost linear behaviour of the module simplifies the implementation of simple Maximum-Power-Point-Tracking (MPPT) electronic circuit to use the available power in an efficient manner, charging the vehicle batteries at full available power, as presented before [30].

1.3. Heat Pipe Working Principle

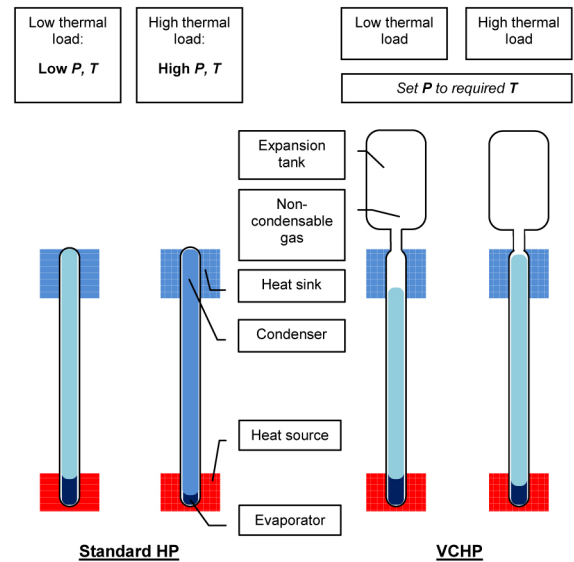


Figure 1. Comparison of Standard and Variable Conductance Heat Pipes under variable thermal load

Although very simple in their working principle, HPs (heat pipes) are of relatively recent use in industry [32]. A basic Heat Pipe consists of a sealed upright pipe containing a small portion of phase-changing fluid (see Figure 1 - left). The remainder of the inner volume of the pipe is occupied either by the thermal fluid vapour or by a mix of vapour and non-phase-changing gas (such as air). Due to gravity, the fluid rests at the bottom of the pipe (the heat source region, or evaporator of the HP), where it will be heated and boiled under the action of the heat crossing the pipe walls through conduction. The vaporized fluid will eventually condense at the upper part of the pipe wall releasing its heat to the heat sink. Once condensed, the liquid droplets will fall back to the bottom of the pipe, completing the cycle and being ready to vaporize and condense over and over again.

A Heat Pipe will only start transferring heat from the hot source to the heat sink once the boiling temperature of the fluid has been achieved. This boiling temperature is not a static value but depends on the actual pressure of the fluid inside the HP (the pressure also changes during operation).

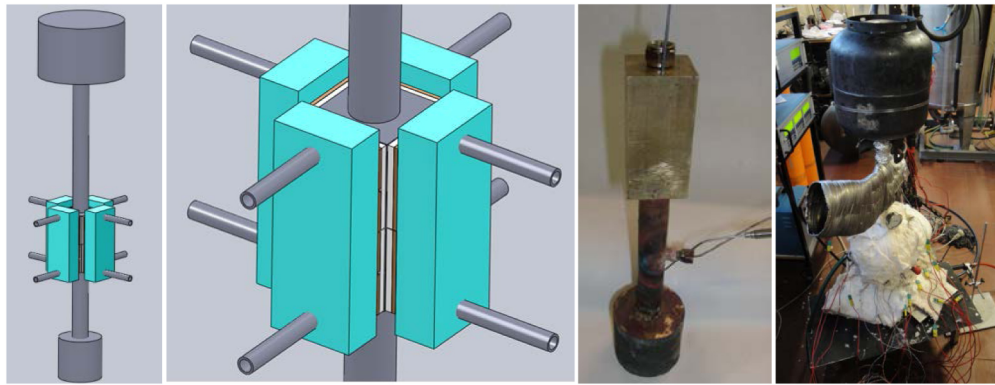


Figure 2. Basic Proof-of-concept model used in the current work

1.4. Variable Conductance Heat Pipes (VCHPs)

One way of controlling the phase changing temperature of a fluid would be to control its pressure. If the pressure could be kept constant at a specified value, then a certain HP operating temperature could be regulated. The use of an expansion tank attached to the top of the HP will enable this outcome (Figure 1- right). Therefore, pressure would not build up during operation as it would in a standard HP and the boiling would not be hampered by an excessive increase of pressure. Such a system is called a Variable Conductance Heat Pipe (VCHP) and has been used in the current work.

The comparison between the response of standard HPs and VCHPs for low and high thermal loads is outlined in Figure 1 (top). It is expected that with this system the HP will be able to work at a specified temperature. This will be made by adjusting the HP pressure to control the boiling temperature (the operating temperature of the VCHP) regulating it to the maximum allowable TEG temperature, thus optimizing the heat transfer rate of the system while protecting the system from over-heating.

2. EXPERIMENTAL PROCEDURE

2.1. Basic Proof-of-Concept Model

In order to test the concept of TEG heat management through heat pipes a basic experimental model was built (See Figure 2). This model is in no way optimized for direct application in real vehicles but has been built in order to provide some insight into the thermal performance potential of heat pipe-based thermal management of a thermoelectric generator. A 22mm diameter copper pipe serves as the HP body that links the HP evaporator and condenser. It is soldered at the lower end to a wide diameter solid brass base with a hole in the continuity of the pipe. This block serves as the HP evaporator on which the heat source substituting exhaust heat (a blowtorch flame) is directed (see sketch in Figure 3). The upper end of the copper pipe is connected to another brass block with square section and drilled in continuity with the pipe hole. The inner surface of the block

acts as the HP condenser and there are 8 thermoelectric modules attached to the exterior faces of the block. On the outer face of these modules 4 aluminium flat ducts are attached to act as the heat sink of the modules. Inside these ducts cool water is forced to flow at a specified rate.

The top of the HP condenser block is connected to a large cylinder vessel (20 L). The purpose of this vessel is to maintain the HP pressure at the specified value, therefore setting the required temperature of phase change of the thermal fluid (water). This pressure is pre-regulated by injecting air into the system with an air compressor.

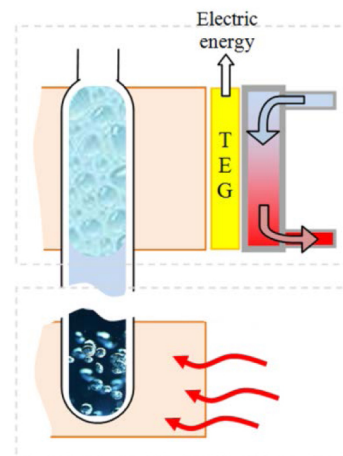


Figure 3. Outline of the operating principle of the basic proof-of-concept model

Thermocouples were placed at various locations to measure the temperature and determine heat fluxes throughout the prototype. Care was taken to minimize the effect of contact thermal resistance, using thermal grease. It was also possible to assess the maximum potential for the supplied heat by looking at the temperatures of the pipe connecting the HP to the large vessel. If some of these temperatures were below the boiling temperature for the set pressure and others were at the boiling temperature, we could be sure that the condenser was working fully and there was