

Influence of Heat Pipe Operating Temperature on Exhaust Heat Thermoelectric Generation

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ABSTRACT

Increasingly stringent targets on energy efficiency and emissions, as well as growing vehicle electrification are making attractive the electric recovery of the energy normally wasted through the tailpipe of Internal Combustion Engines. Recent developments in thermoelectrics (TE) may soon make them a viable solution for such applications [1].

This team has been exploring the potential of using TE modules in combination with variable conductance heat pipes for transferring the exhaust heat to the generator with very low thermal resistance and at a constant, prescribed temperature. This passive temperature control eliminates the need for by-pass systems in the event of temperature overshoots.

The operating temperature of a generator should be as high as possible in order to maximize the Seebeck effect. However, currently available modules are temperature limited. Moreover, the higher the HP temperature the less the usable thermal power at the exhaust will be (heat can only be transferred to from a hotter to a colder body).

The present work assesses both theoretically and experimentally the influence of the HP temperature in the electric output of a thermoelectric generator. A small diesel engine and a generator were tested and it was found that a high HP operating temperature is only limitative for performance in the cases where low exhaust temperature and low engine power are present. In those cases it is possible to estimate an optimal HP temperature in order to maximize power output. The combined use of Seebeck modules and heat pipes was found to be highly advantageous in various ways.

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INTRODUCTION

The harvesting of the wasted energy in Internal Combustion Engines (ICE) is now becoming more and more attractive as fuel economy and emissions targets [2;3] are getting evermore challenging for automotive industry OEMs. In fact, over one third of the energy content of the fuel is normally wasted through the tailpipe of the ICE [4;5], with a similar amount being lost in other ways, namely the cooling system. In comparison to the cooling heat, the exhaust energy has a much better recovery potential due to its high temperature level.

Energy waste may be reduced firstly by improving the thermal efficiency of the ICE with strategies such as over-expansion, as explored by the team [6;7] or by converting it into electricity, something increasingly attractive given vehicle electrification trends.

Electric turbo-charging/compounding, Organic Rankine Cycle (ORC) turbines [8;9] and Thermoelectric Generators (TEGs) based on the Seebeck effect [1] have been tested in heavy duty applications in the past. ORCs have the highest

recovery potential [9] but are still difficult to downsize for light duty vehicle applications [10].

Despite its still low efficiency, state-of-the-art TE modules exploring phenomena such as quantum confinement are claiming efficiencies above 10% [11]. TEGs are reliable as they don't have moving parts and they are very small in volume. Moreover, they currently stand as the only practical option for low power waste heat recovery applications since they are intrinsically scalable. Major OEMs like Honda [12] and BMW [13] have been testing this technology, some with targets of 5% improvement in fuel economy.

But the currently most significant obstacles for TEG adoption in exhaust applications are their limitations in operating temperature, power density and cost [10]. The current power density and cost restraints of TEGs may soon be overcome by the use of low thickness TE modules combined with very low thermal resistance heat paths [14]. Solutions for controlling the operating temperature of TEGs with low thermal resistance and high reliability (no moving parts) have been proposed by the team using heat-pipes. This

included both theoretical and experimental work with several proof-of-concept prototypes [15, 16, 17, 18]. This solution avoids the use of by-pass systems as the source heat is converted to the required temperature level.

The use of a phase changing fluid contained within Heat Pipes (HP) to transfer the heat from the exhaust gases to the thermoelectric devices is convenient in several ways [19]. On one hand, Boiling and Condensation are among the most effective heat transfer mechanisms available. Additionally, the possibility of regulating the operating temperature of the HP (the boiling point of its fluid) provides passive protection to the system in terms of overheating, thus eliminating the need for wastegates/bypass valves.

Ideally, the heat directed to the TEG should display the highest possible temperature that the modules can withstand in order to maximize the Seebeck Effect (voltage generated increases with the increase of the temperature differential across the thickness of the TEG modules). However, currently available modules are temperature limited. Furthermore, the temperature of the HP fluid has to be suitable for the exhaust gas conditions. Too high and the temperature difference between gases (at low power conditions) and HP will be too small to provide enough power. Too low and the TEG efficiency will drop below usefulness. For each exhaust condition there will be an optimal HP working temperature.

Previous work published by the group has illustrated the potential of TEGs with HP assist by testing several proof-of-concept prototypes. The present work assesses the influence of HP temperature on TEG performance both theoretically and experimentally.

Heat Pipes

A Heat Pipe (HP) is a thermal device with an extraordinary degree of heat transfer potential, as it uses one of the most efficient modes of heat transfer, the phase change [19]. In short, a heat pipe (Fig. 1) is a tube where in one extremity a liquid (can be water) boils and on the other end it condenses, transferring an enormous amount of heat from the boiling end to the condensing end. A large flow of fluid travels in vapor form (from vaporization to condensation ends) through the inside of the pipe and in liquid form, by gravity, attached to the walls.

The HP depicted in Fig. 1 has only one fluid, in vapor and in liquid form, obviously at saturation conditions. This means that the pressure and the temperature will change according to the outside temperature and according to the thermal power it is subjected to. Therefore, it is not possible to control the temperature at which the heat transfer will occur because increased vapor generation will easily raise the inner pressure and thus also raise the saturation temperature. For that we need to control the HP pressure independently of its heat flux.

This device is called the Variable Conductance Heat Pipe (VCHP), and it incorporates an expansion tank as well as a non-condensable gas in its interior at a prescribed pressure.

The expansion tank has the ability of accommodating variable vapor content during variable load operation without significant pressure increase. Now, if the non condensable gas pressure is kept constant, so will be the phase-change temperature of the working fluid. This latter temperature will be the HP temperature. With this appliance it is possible to accomplish the goal of limiting the temperature at which the heat is supplied to the TEG and tune this temperature to an optimum. The VCHP proposed in this work is of this type.

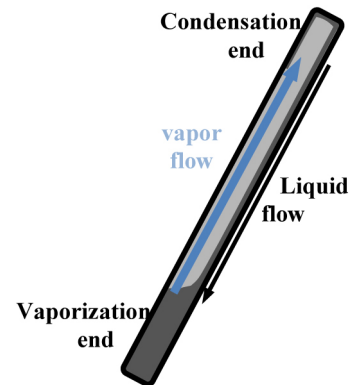


Figure 1. Working principle of a basic Heat Pipe

Fig. 2 displays the comparison of Standard and Variable Conductance Heat Pipes under variable thermal load.

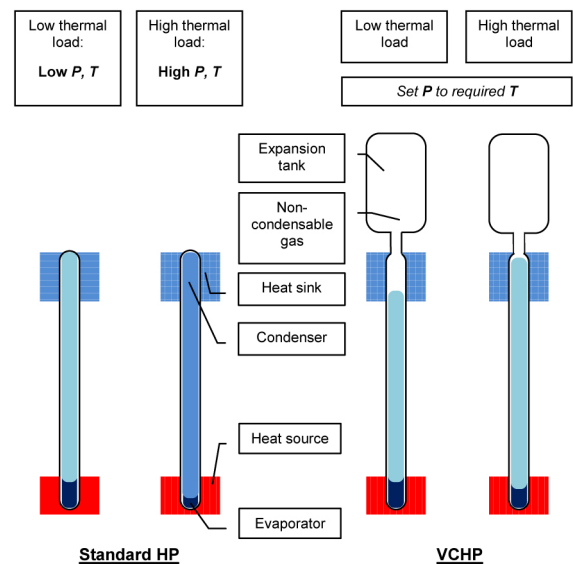


Figure 2. Comparison of Standard and Variable Conductance Heat Pipes under variable thermal load

The Variable Conductance Heat Pipe owes its name to the fact that the active area of the condenser (the area reached by the vapor) will vary according to the thermal load. In fact, as more thermal power is available, a higher amount of vapor will be generated. This vapor mass will push the gas further up, taking its place pushing it out of the condenser region, and therefore will reach a bigger area of the condenser. Under

these conditions, the active area of the condenser will vary according to thermal load providing the analogous of a variable conductance medium.

Additionally, it would be possible to envisage a device with actively controllable pressure by means of a pressure adjustable membrane bladder, therefore allowing different working temperatures. This may be interesting to enhance the heat transfer levels for different exhaust conditions (different engine loads and speeds) but would increase system complexity. If the temperature for the phase change is set at the maximum (allowed by the TEGs), then the heat transfer will be very limited at low exhaust temperatures. It is therefore advisable to find the ideal HP temperature so as to maximize electric output. After having illustrated the potential of using temperature controlled thermoelectric generation with heat pipes in previous works, the present work explores precisely the issue of optimal heat transfer temperature in such systems.

The use of a very small 10 hp Diesel engine with a generator with only 12 thermoelectric modules illustrates the scalability of this type of technology. Naturally, bigger engines and generators will be likely used in other applications of this technology in the future.

EXPERIMENTAL PROCEDURE

A proof-of-concept model of a VCHP device has been built in order to assess the potential for heat recovery from the exhaust system of a small Internal Combustion Engine (ICE). It is an evolution of a previous model studied before [16].

The evaporator end of the VCHP is immersed in the exhaust stream of a small single-cylinder Diesel engine. This evaporator consists of a series of finned copper pipes (see Fig. 3). We used the actual pipework from a combustion chamber of a small hot water boiler. It has 7 fins per centimeter. This system is seen at the bottom of the global apparatus seen further ahead in Fig. 6.

As seen in Fig. 3, the evaporator has 6 finned pipes that are all interconnected at the bottom (to equalize liquid level), with 8 mm outer diameter and 0.5 mm of thickness.

These 6 copper pipes are connected to three upper copper blocks, acting as condensers. The vapor generated at the evaporator will rise and condense at the blocks, falling back (due to gravity) to the evaporator. The HP fluid used was water, filling the length of the evaporator pipes that is immersed in the exhaust gas flow. Using water as working fluid is recommended only for mild temperatures since increasingly high pressures are needed for higher HP operating temperatures (for instance, obtaining a 200 °C water boiling temperature would require pressures in excess of 15 bar). The authors have tested previously other fluids besides water. Namely, a fluid called DOWTHERM A was used for the higher temperature range [16]. This fluid has a phase change temperature around 250 °C at atmospheric

pressure. Fluids recommended for other temperature ranges are proposed in [19].

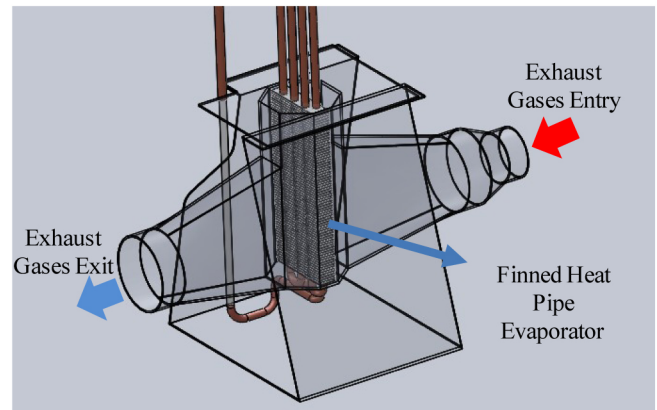


Figure 3. Drawing of the exhaust gases duct with the HP Evaporator inside.

No wick covering the inner HP surface was deemed as necessary in this phase, as the HP can operate solely on gravity. Consequently, the HP heat exchanger solution adopted does not pose the cost issues frequently associated with the more customized wicked HPs like those found in aerospace applications [19].

TEG modules were placed on the outer surface of these condenser blocks, “sandwiched” between them and the water cooling ducts. These condenser blocks, shown in Fig. 4, are 20mm thick solid copper blocks with an area that fits two vertically aligned thermoelectric modules (RS Amidata ref. 6937116 with dimensions $62 \times 62 \times 5.3 \text{ mm}^3$) on each face. The blocks were drilled with two different diameter holes, as shown. The bottom of the first block has six 8 mm holes, where the 6 heat pipes have been attached. These six 8 mm holes extend up to two thirds of the length of the block and are intercepted by three 16 mm holes drilled from the top of the block down to a depth of two thirds of the total block height. The condensation of the working fluid occurs on these inner surfaces.

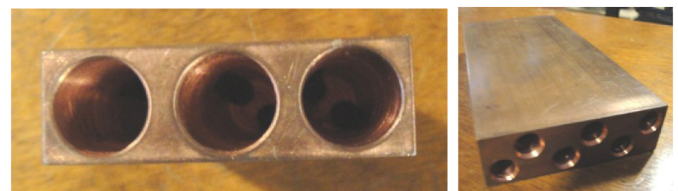


Figure 4. Upper view (left) and lower view (right) of the HP condenser blocks

Of course, an optimized commercial version of the concept need not use expensive bulk copper (it has been used here to easily obtain low thermal resistances). The aim will be to increase the condensing area and reduce thermal

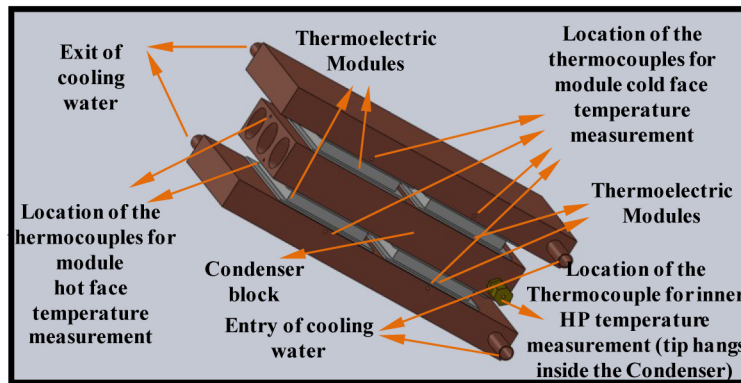


Figure 5. One of the three HP condenser blocks each one attached with modules on both sides and external cooling ducts.

resistance (either obtained with high conductive materials or low thickness ones).

On the outer (cold) face of the TEGs water ducts were placed, as shown in Fig. 5. These were also made from solid copper blocks (15 mm thick) drilled with seven 6 mm holes, through where the cooling water would flow. To maximize the convective heat transfer the contiguous channels were connected in zig-zag in a series configuration so that water speed and turbulence could be maximized.

Again, this proof-of-concept system could be optimized for the commercial application by using less bulk materials, lower thicknesses and wider exchange areas.

Sharing the engine's cooling system for cooling the modules may not be a good solution since its temperature is too high (loss of temperature differential). However, a dedicated low temperature cooling system does not seem to be ideal either, as it could have some energy consumption and would add complexity to the system. This issue has still not been addressed in the current work, but some passive cooling system would be envisaged for future work. This could consist on a finned air cooled heat sink in contact with the vehicle's external air flow. Even better, a heat pipe with an externally finned heat sink at the HP condenser.

Fig. 6 shows a global view of the apparatus (the complete system is seen in Fig. 8). Comparing with the outline of Fig. 2 the heat source is the exhaust gas flow that crosses the evaporator as seen previously in Fig. 3. The condenser consists on the group of three blocks, each with 4 thermoelectric modules attached. The face of the modules attached to the condenser blocks (called the hot face of the modules) is the heat sink of the HP (the medium through which the heat is retrieved from the system). On the other hand, the heat absorbed by the modules is subsequently channeled to the exterior by the cooling ducts that are attached to the outer face (called the cold face) of these same modules, as depicted in Fig. 5. For clarity these ducts are missing in Fig. 6 so that the modules may be seen.

Three 16 mm copper tubes make the connection between Block 3 to 2, and the connection from that block to Block 1 (the top block) is again made by six 8 mm tubes (Fig. 6).

A collector, located at the top of the system, connects the pipes from the top block (Block 3) to a 20 L expansion tank that ensures constant pressure (and thus operating temperature) of the system irrespective of load. Since this is still a proof-of-concept apparatus no calculations to optimize the tank capacity have been made, but the results confirmed the isothermal operation of the system. The Clausius - Clapeyron relation (which relates pressure, temperature and volume differentials for vapor) could be used to do this.

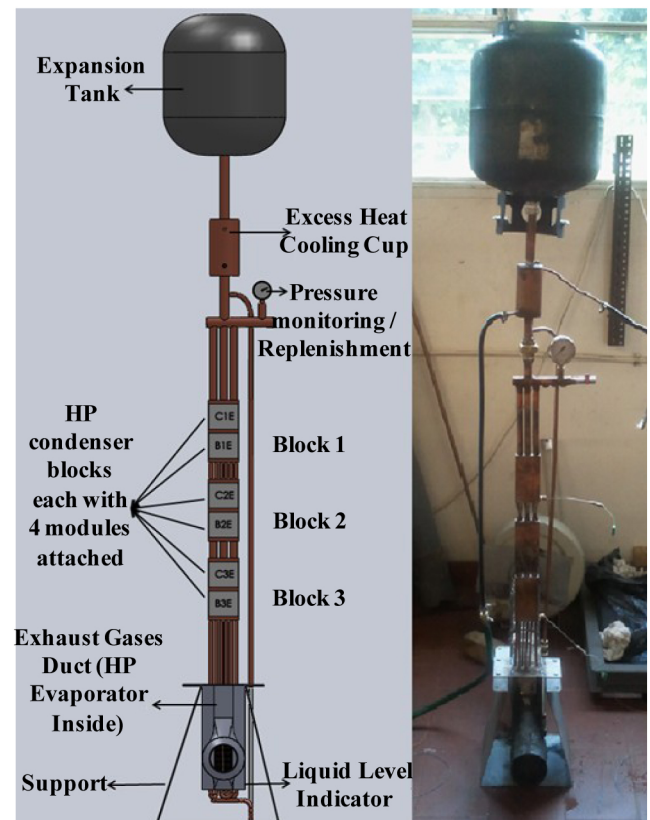


Figure 6. Design and photograph of the apparatus

In the event of an excessive load the vapor region will expand extending beyond the condenser blocks. To avoid the risk of evaporator dry out during these high power events, a