

Waste Heat Energy Harvesting for Improving Vehicle Efficiency

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ABSTRACT

Currently, in the typical internal combustion engine, approximately one third of fossil fuel combustion by-product is wasted heat. In the continued effort to improve fuel economy, one area that is being researched today is the harvesting of wasted energy to increase vehicle efficiency.

This paper will address how heat emitted by exhaust systems can be captured and used to increase vehicle efficiency. Overall we will compare energy content in the exhaust manifold and exhaust underfloor mid-vehicle position, where potential exhaust heat exchanger concepts can reside. These heat exchanger concepts are designed primarily to capture heat from these locations and transfer the energy for increased passenger heating and comfort during cold conditions and/or supplement other improvements in powertrain efficiencies. An analysis of the energy exchange to the heated fluid is compared in the exhaust manifold and underfloor position respectively. Issues associated with heat energy harvesting from a typical exhaust system will be presented in detail, with suggestions for improving future systems.

The innovation behind the Faurecia Exhaust Heat Recovery System (EHRS) performance will be presented in detail for exhaust underfloor installation. Rather than throw off the heat emitted by exhaust systems, this innovation uses a gas/water heat exchanger to supplement the heating up the engine coolant. As a result, exhaust heat helps the vehicle interior to warm up in 25 percent less time than with conventional systems. This process can provide a shorter heating time for the powertrain as well. When the powertrain temperature increases more rapidly after start-up, fuel consumption improves.

Adaptation of this technology is also under development to boost the fuel savings of hybrid vehicles by increasing the duration of all-electric driving in the winter. More rapid warming decreases power demand and enables vehicles to travel farther on their electric motors. This system offers the potential of an 8 to 10 percent improvement in fuel economy for hybrid vehicles, with an environmentally friendly solution that replaces auxiliary heating systems.

INTRODUCTION

Studies have been conducted and document waste heat generated from the typical internal combustion engine to be as much as 30 percent of the energy content burned within the engine [1 - 2]. This excess heat is usually conducted, convected and radiated to the vehicle body and ultimately transferred to the environment as waste heat. In prior studies [2], the heat generated at the tail end of the vehicle out of the exhaust tailpipe could be as much as 2 - 3kW. As we move toward the vehicle's engine, the energy content rises appreciably towards a favorable number; for example a typical naturally aspirated 4 cylinder gasoline engine may approach up to 20kW. Any percentage of this energy that can be captured within a given location can be used to beneficially increase vehicle efficiency.

One method of using the captured heat is to transfer it directly to the engine coolant system. The resulting net increase in the energy content can be used to heat up the cabin and also the powertrain system's vital fluids. The latter method is geared toward viscosity modification of the powertrain fluid. This enables a lower coefficient of friction of the lubricant between moving powertrain components during very cold conditions and also during the critical engine start-up procedure.

The method of capturing heat to heat up the cabin for occupant comfort has the potential to offset other methods of increasing passenger comfort during cold conditions. The most widely used technology currently being leveraged for heating the passenger compartment includes fuel fired heaters and positive thermal coefficient (PTC) heaters. Both methods of heating the passenger compartment in a typical vehicle suffers a number of disadvantages, primarily that they both use a fair amount of fuel on top of the fuel used for power propulsion. For the case of the fuel fired heaters, fuel is being combusted to generate heat, which is either transferred directly to the cabin or to the coolant system [2]. For the case of PTC heaters, the heat generated is typically being transferred directly to the cabin. In the realm of electrification of the vehicle, energy harvesting plays a more significant role in increasing the efficiency of the vehicle. For hybrid vehicles specifically, which have parallel power propulsion from the internal combustion engine and electric motor, the major proponent of fuel efficiency is simply not to propel the vehicle using the internal combustion engine. However, in order to generate heat for the cabin during cold conditions, a heat source is needed. A PTC heater can be used to generate supplemental heat for cabin heating, but PTC heaters typically use precious electric energy, which is either stored in the hybrid vehicle's battery or directly from the engine generator/alternator. In the near term, for these vehicles, exhaust heat recovery is a technology that can be used immediately to produce an appreciable amount of fuel efficiency to the vehicle.

The method employs a heat recovery system (usually gas to liquid heat exchanger system) installed within the exhaust system, which captures the heat from the exhaust during internal combustion engine operation cycle (during cold start procedures to warm up coolant and catalyst). Supplementing the heat generated from the internal combustion engine, the energy can then be transferred to the cabin. This accelerates the cabin heat up temperature target set point, which when achieved allows the internal combustion engine to be cycled down and the vehicle can rely strictly on battery powered propulsion.

The location along the exhaust system to install the heat recovery system is a delicate discussion. The heat recovery system is a sizable component similar to a resonator assembly in a typical exhaust system. Since energy content is higher closer to the engine, the heat recovery system should be installed closer to the engine. However, typically there will be after-treatment devices, which are also situated close to the engine in order to reap the benefit of higher energy content for faster warm-up. In this case, the heat recovery system has to be post after-treatment device so as not to affect emissions performance during the critical warm-up stage.

ENERGY ANALYSIS

NEDC CYCLE (2.0L NA)

The New European Drive Cycle (NEDC) procedural test cycle were used as a means to quantify exhaust gas temperature for this study. The NEDC cycle is used to quantify fuel economy and emissions on a vehicular level. The features of the NEDC cycle consists of urban driving with low engine speed and low exhaust temperature and is a good transient test cycle to quantify transient thermal response in the exhaust system. During a normal NEDC procedural test cycle, whereby the powertrain is allowed to dwell in 20°C, the majority of the powertrain components and the exhaust system will be between 20°C and 30°C. In this case, for a 2.0 L engine, as soon as the engine is turned on the heat generated by the engine is mostly absorbed by the thermal mass of the metallic components within the powertrain system before it is being transferred to the exhaust gas. However, from [Figure 1](#) below, it can be seen that at the engine manifold that exhaust gas temperature can be very high, up to 750°C. This is corresponding to the vehicle speed and load applied to the vehicle during the test cycle. As we move along towards the middle of the vehicle, where EHRS is ideally situated, the exhaust gas temperatures are far lower compared to the exhaust gas temperature at the engine manifold. The average difference is observed to be as much as 300°C.

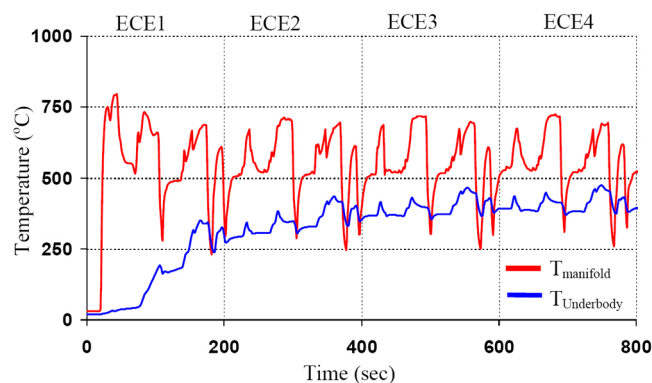


Figure 1. Exhaust gas temperature for 2.0L NA engine in NEDC cycle

Further calculating the content of energy (Eq. (1)), for the first 200 seconds is shown in [Figure 2](#). From the time when the engine is started until about 20 seconds into the test cycle, there is no heating power available within the exhaust system. However, during the first critical 200 seconds of the NEDC cycle the exhaust gas temperature exiting the manifold quickly climbs as referenced in [Figure 1](#). It is observed that the maximum available heating power within the exhaust system is about 20kW. This amount of heating power fluctuates very rapidly over time due to the transient velocity and load exhibited on the vehicle during the test cycle. The effort to improve upon fuel efficiency is concentrated mainly in the critical 200 seconds of the vehicle.

$$\dot{Q}_{Exhaust} = \dot{m}_{Exhaust} C_{P_Exhaust} (T_{Manifold} - 25^{\circ}C) \quad (1)$$

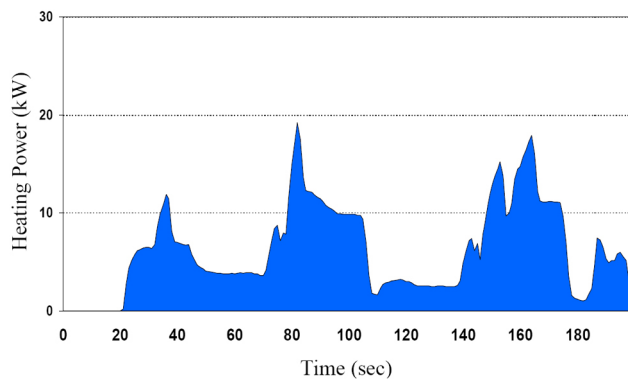


Figure 2. Energy content at manifold for 2.0L NA engine in NEDC cycle

To further segregate and investigate the amount of heating power throughout the exhaust system, Figure 3 shows the segregated available heating power for each separate United Nations Economic Commission for European (ECE) cycle (1 to 4) and also positions within the exhaust system respectively. Four positions were recorded at the engine manifold (MANIFOLD NA), post close coupled catalyst at 40cm, 80cm and 100cm respectively (POSTCAT NA 40cm, POSTCAT NA 80cm and POSTCAT NA 100cm). The heating power is the average at each section and it is taken at average for each ECE cycle. When comparing each section within the exhaust system it can be seen that the available heating power drops dramatically away from the engine manifold within the critical ECE1 position. In particular, when at the positions of POSTCAT NA 80cm and POSTCAT NA 100cm, the available heating power drops as much as 60 percent compared to MANIFOLD NA and POSTCAT NA 40cm.

Looking at ECE2 and ECE3 portions, the effect of heating power loss along the exhaust system is less pronounced compared to the heating power loss in ECE1 portion. During ECE 2 and ECE3 cycle, majority of the powertrain system components and the exhaust system have risen to its operating temperature. Here, the energy content in the exhaust gas is not primarily used to heat up metallic components. Furthermore, by analyzing the capability of the heating power along the exhaust system from the manifold downwards to the underbody of the vehicle, it can be seen that the maximum amount of heat that can be recovered post manifold location is about 30 percent less, which is in the 3 - 4 kW range. In this 3 - 4kW range, the potential of extracting a portion of heating power decreases rapidly, affecting the importance of the efficiency of the heat exchanger.

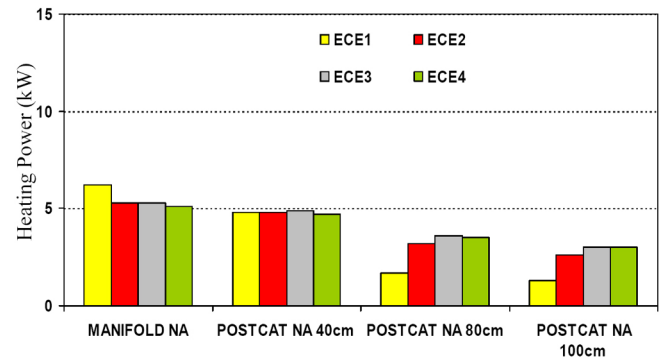


Figure 3. Segregated energy content for 2.0L NA engine in NEDC cycle

COLD FTP CYCLE (2.5L NA HYBRID)

Under the standard cold Federal Test Procedure (FTP), a vehicle equipped with a hybrid engine exhibits very different exhaust energy profile compared to a vehicle equipped with a NA engine. Furthermore, a hybrid, especially one equipped with a parallel drive profile in which the electric motor can be used to propel the vehicle with the engine entirely turned off, presents an interesting investigation into the available heating power of the exhaust system. Figure 4 shows the exhaust temperature profile of a 2.5L NA hybrid conducted under the cold FTP cycle. The exhaust gas temperature is recorded post after treatment device in the underbody location of the vehicle. The mass flow rate of the exhaust indicates the running order of the engine. During the first 500 seconds of the FTP cycle, the engine is turned on primarily to warm up the ancillary components like the powertrain system and the cabin of the vehicle. Thereafter, the engine is needed for periodic propulsion of the vehicle. During these times, the temperature of the exhaust system drops significantly from average 500°C to average 350°C (Figure 4).

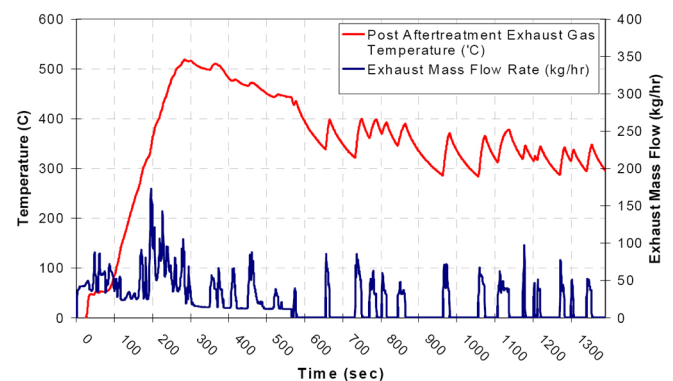


Figure 4. Exhaust Gas Temperature for 2.5L NA Hybrid in Cold FTP Test Cycle

Further calculating the available heating power of the exhaust in the underfloor position of the vehicle (Figure 5), the majority of available heating power occurs in the first 550