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Advanced Waste Heat Recovery Systems within Hybrid Powertrains

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Abstract

A waste heat recovery system (WHRS) is very well known to provide no advantage during the cold start driving cycles, such as the New European Driving Cycle (NEDC), which are used for certification of emissions and assessment of fuel economy. Here, we propose a novel integrated WHRS using the internal combustion engine (ICE) coolant passages and an exchanger on the exhaust working as pre-heater / boiler / super-heater of a Rankine cycle. The expander is connected to an electric generator unit (GU), and the pump is connected to an electric motor unit (MU). The vehicle is also fitted with an electric, kinetic energy recovery system (KERS). The expander and condenser are bypassed during the first part of the NEDC when the vehicle covers the four ECE-15 (Economic Commission for Europe - 15) - UDC (Urban Drive Cycle) segments where the engine warms-up. Only after the engine is fully warmed up, during the last part of the NEDC, the extra urban driving cycle (EUDC) segment, the expander and condenser are activated to recover part of the coolant and exhaust energy.

Keywords: internal combustion engines, waste heat recovery systems, kinetic energy recovery systems, vehicle hybridization

1. Introduction

In a conventional gasoline engine, at its optimum, only one third of the fuel energy flow is converted into mechanical energy, the remaining two thirds is wasted mostly in the exhaust and in the coolant. Far from this optimum, at part load, the waste energy is much larger. The recovery of the exhaust and coolant energy is, however, particularly difficult, as the actual recoverable energy is usually a small fraction of what is theoretically available, and its harvesting is challenging and paid at the price of increased backpressure, increased thermal inertia, and packaging and weight downfalls. During cold start transients, a waste heat recovery system (WHRS) generally results in worse rather than better fuel economies. The objective of this work is to discuss the advantages of an ad-hoc redesigned engine with an integrated WHRS may have in cold start driving cycles.

In this exercise, the waste heat recovery system (WHRS) is designed for an in-line four turbocharged gasoline engine fitted to a hybrid electric vehicle (HEV). The HEV has an electric, kinetic energy recovery system (KERS) with driveline motor-generator unit (MGU). The turbine on the exhaust limits the amount of exhaust energy recoverable, and a three-way-catalytic converter (TWC) is also fitted to the exhaust. The turbocharger shaft is connected to an electric MGU. The WHRS has an expander connected to an electric generator unit (GU) and a pump driven by an electric motor (EM). The energy balance of an internal combustion engine (ICE), the thermal transient of passenger cars powered by ICEs during cold start driving cycles, the kinetic energy recovery and the opportunity to recover the waste heat are covered with references [1-17]. The reader is referred to these publications for additional background information.

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2. Waste Heat Recovery Systems and Cold Transients

A WHRS is in principle enabler of much higher fuel efficiencies that, however, completely disappear during cold start driving cycles, as cars equipped with a WHRS fitted to an ICE generally fail to provide benefits during certification cycles such as the New European Driving Cycle (NEDC).

The cold start NEDC includes four ECE-15 (Economic Commission for Europe – 15) – UDC (Urban Drive Cycle) segments representing city driving repeated without interruption, followed by one EUDC (Extra Urban Driving Cycle) segment representing highway driving. Before the test, the vehicle can soak for at least 6 hours at a test temperature of 25 °C. The ECE-15 is an urban driving cycle characterized by low vehicle speed, low engine load, and low exhaust gas temperature. The EUDC segment has been added after the fourth ECE-15 cycle to account for more aggressive, high speed driving modes. As the cycle is only 1180 s long, conventional internal combustion engines (ICE) within traditional powertrains are not fully warmed up before the end of the cycle. With hybrid power trains, the fully warmed up conditions are further delayed.

The WHRS is of interest, particularly for steady, high loads situations after full warm-up, but it suffers largely at cold transients that forms a considerable part of the certification test. The downfall of a traditional WHRS is the large inertia and the increased weight coupled to the packaging issues. A possible solution is to better integrate the WHRS with the engine, packaging all the components in the engine bay. This certainly reduces the increased thermal inertia and the weight penalties, but it does not completely address the cold start issues. To be effective during cold start, the engine must be completely redesigned to have the coolant passages working as pre-heater.

During the cold start of the NEDC, the first urban sectors do not have too much energy to fully warm up the engine. The energy available increases during the extra urban sector closing the driving cycle, but often the engine is not fully warmed-up at the end of the driving cycle. To solve this issue, it is then important to use first the energy of the exhaust gases to quickly warm-up metal and media. Based on a Rankine liquid-vapor cycle, a WHRS is based on a pre-heater, a boiler/super heater, an expander, a condenser and a pump. Expanders and pumps mechanically linked to the crankshaft have the disadvantages of operating correlated to the speed of rotation of the engine. In a turbocharged engine, the energy of the coolant, the oil cooler, the air cooler after the compressor and the exhaust gases are all theoretically available to be recovered. However, the harvesting is particularly troublesome mostly for thermodynamic and backpressure effects in addition to weight and packaging issues. Therefore, focus should be given to coolant and exhaust gas waste heat.

The cold transients are the Achilles' heel of every WHRS, as WHRS make the cold transient, usually longer rather than shorter for the increased thermal inertia. This is the reason why the recovery of the theoretically large amount of energy is almost nowhere to be seen in passenger car applications. WHRS so far are a working feature only of large stationary internal combustion engines for power generation or marine applications.

3. BMW Turbo-Steamer and Chevrolet Malibu Hybrid Exhaust Gas Heat Recovery

The most promising WHRS concept developed so far for passenger car applications is certainly the BMW Turbo-Steamer [1-3]. The BMW Turbo-Steamer is a combined cycle engine using a steam engine with water as the working fluid to recover the waste energy from a conventional internal combustion engine. This design includes multiple circuits and many additional heat exchangers, pumps and expanders thus substantially increasing the weight and inertia of the system. The Turbo-Steamer was fitted to the exhaust and the cooling system of an otherwise standard 1.8 liter in-line four, naturally aspirated, gasoline engine. The recovery of the waste energy was estimated to improve the fuel efficiency of up to 15%, with advantages increasing at higher, steadier speeds. However, the improved efficiency was never achieved during the cold start certification cycle, where the system was a disadvantage. The major shortfall of the BMW Turbo-Steamer was the extreme complication and the use of 3 separate circuits to recover the exhaust and coolant heat of an otherwise traditional internal combustion engine, translating in many heat exchangers and other system components, and many very long pipes substantially complicating the vehicle layout, increasing weight and difficult to package. This design produces high thermal inertia to the recovery system, therefore, not performing well during transients, thus reducing efficiency in the steady state operation.

To achieve a much quicker warm-up, during cold start, the WHRS expander and the condenser must be bypassed. This permits a quick warming of the coolant, translating in a quick warming of metal and media for reduced frictions in a significantly shorter transient. The latest 2016 Chevrolet Malibu Hybrid [18] (naturally aspirated, not turbocharged) features an Exhaust Gas Heat Recovery (EGHR) system to accelerate the coolant heat up and warming the battery pack. This system is simply made up of a heat exchanger placed in the exhaust gas transferring part of the exhaust waste energy to the cooling system. When the engine is warmed up, the exhaust gas is diverted and this exchanger is bypassed. The main benefits of the recovery of some heat wasted in the exhaust during cold start transients is a quicker warm up of metal and media. Cold starts transients are indeed characterized by metal, oil and coolant temperatures that are much lower than the fully warmed up values all over the cycle. The EGHR is not used to generate energy from the exhaust waste heat. Nevertheless, this still reduces fuel consumption and emissions thanks to the faster warmed up of the coolant. As the actual waste heat recovery at the expander can't be performed efficiently before the engine is fully warmed up, during short cycles, this strategy for a quick warm-up works more efficiently than the adoption of a full WHRS.

4. Electric Kinetic Energy Recovery System and Turbocharger

During a driving schedule, a passenger car must accelerate and decelerate. In a traditional powertrain, the power of the acceleration is delivered by the ICE, while the power for deceleration is provided by the friction brakes. In terms of kinetic energy of the vehicle, the ICE increases the kinetic energy burning fuel, and the friction brakes dissipate into heat the kinetic energy. With KERS, during braking the kinetic energy may be stored to be used, then during the following acceleration to replace the ICE fuel energy supply. A KERS is available in mechanical, electric, electromechanical or hydraulic flavors, but those most widely used are electric. In an electric KERS (E-KERS), a motor/generator unit (MGU) is connected to the driveline and the energy storage for kinetic energy recovery, charging the energy storage during decelerations and buffering the engine during the following acceleration, coasting or stop. Regenerative braking is essential for fuel consumption reduction, especially during urban driving cycles. However, in terms of engine warm-up, as the KERS reduces the use of the ICE, the warm-up is made longer, and WHRS are less effective during cold start driving cycles in hybrid rather than in conventional powertrains.

In turbocharged engines, the turbocharger's turbine recovers part of the energy of the exhaust gases to compress the incoming air thus increasing the charging efficiency. While turbocharged gasoline engines certainly have much higher specific power and torque than their naturally aspirated counterparts, they do not have better wide open throttle (WOT) or part load fuel conversion efficiencies. Turbocharged engines may still have advantages versus much larger naturally aspirated engines covering driving cycles, as the torque demand may be covered working much higher brake mean effective pressures, and hence with better efficiencies. During cold start driving cycles, especially the urban driving of the NEDC, the energy available to the turbine is typically small, and the compressor is simply not needed. During sharp transients – not the case of the NEDC driving cycle – a standalone turbocharger may suffer of turbo-lag, as the increasing demand of the compressor cannot be matched immediately by the turbine. Connection of a MGU to the turbocharger shaft may cancel turbo-lag, help with low speed torque and aid with some energy recovery. In a hybrid, electric vehicle having energy storage (ES) electric, the turbocharger may be connected to a motor/generator unit reducing turbo-lag times and charging the ES with the extra energy eventually available to the turbine. This opportunity is not used during the cold start driving schedule, but may be beneficial over other working conditions. The motor/generator unit on the turbocharger axis allows the full decoupling of the compressor demand from the exhaust energy recovered in the turbine.

The latest F1 racing engines [19] have shown interesting new directions for the energy harvesting that could be further expanded for more efficient power trains of production cars. New opportunities have been brought forward by the electric hybridization of the power train. The hybrid power unit comprises the turbocharged internal combustion engine (ICE) plus an energy store (ES), a motor-generator unit on the driveline (MGU-K) charging the ES when braking, and boosting the ICE when accelerating discharging the ES. The hybrid power unit also comprises a motor-generator unit on the turbocharger shaft (MGU-H). When the turbine power exceeds the power needed in the compressor, the MGU-H charges the ES. When the turbine power is less than the power needed in the compressor (for example, during sharp accelerations), the MGU-H accelerates the turbocharger by discharging the ES. The turbocharger turbine operation decoupled from the compressor load and charging the ES is one new opportunity to harvest the waste heat in the exhaust. The ICE, the ES, the MGU-H (recovery of extra energy at the turbocharger or assistance of the turbocharger acceleration) and the MGU-K (recovery of the braking energy and ICE boost during accelerations) are well integrated powertrain components. The waste energy recovered by the MGU-H and transferred to the ES is minimal and the MGU-H mostly serves as an anti-turbo-lag device.

5. An Integrated Single Circuit Electric Turbo-Steamer

A single circuit turbo-steamer using the engine coolant passages as pre-heater and a closed-up heat exchanger in the exhaust as boiler/super heater plus electric hybridization may improve the fuel energy usage during steady state and possibly transient operation, but not cold start. Figure 1 presents a sketch of the proposed single circuit turbo-steamer. The expander is connected to the ES through a GU, while the pump is connected to the ES through a MU.

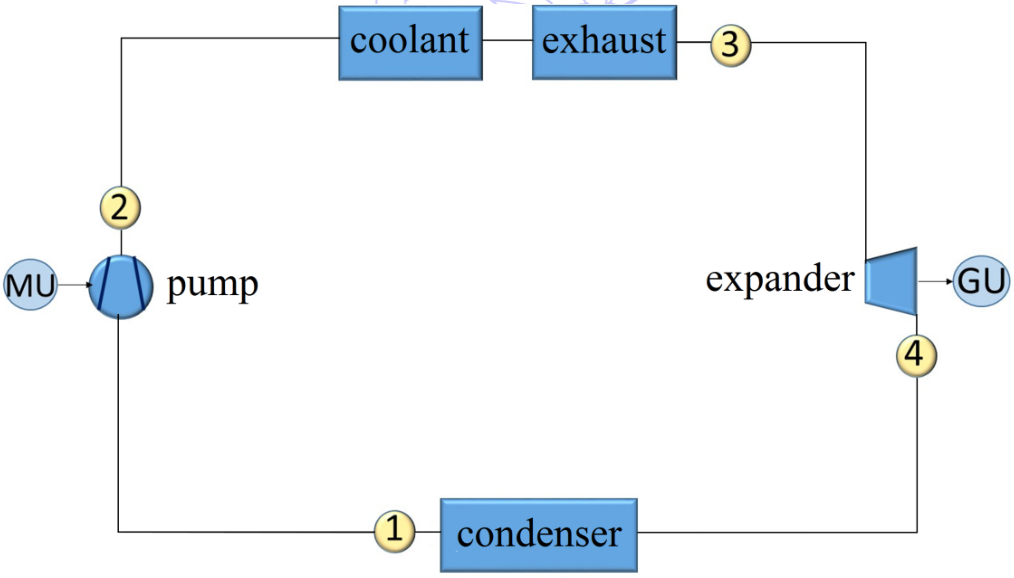


Fig. 1 Sketch of the proposed single circuit turbo-steamer

After the condenser, the water is pressurized by the pump. Then, the water is warmed up moving through the engine coolant passages and finally steam is produced in the boiler/super-heater feed by the exhaust gases. The steam then expands in the expander and it is sent to the condenser.

After the boiler/super heater, the steam expands in a turbine driving a generator unit (GU) charging the electric storage (ES). The steam is then sent to a condenser, then back to the pre-heater gas exchangers by a water pump driven by a motor unit (MU) discharging the ES. As the total mass and volume of the waste energy recovery system is much reduced vs. traditional designs such as [1-3], transients are faster. Heat losses are also reduced for better steady efficiencies. However, the waste heat recovery becomes effective only after the engine has been fully warmed up, and especially when loads are high. Therefore, this system will not work without modifications during the NEDC. A by-pass of expander and condenser may solve the cold start issues.

The integrated single circuit turbo-steamer with the expander and condenser by-pass option we are proposing is expected to deliver same or better than the EGHR performances during transients.

The water pump operated independently from the crank shaft is expected to deliver a quicker warm-up and a better temperature control thanks to the improved match of the cooling needs at any speed and load and media temperatures. The cooling on demand capabilities of the electric water pump (EWP) makes this feature an interesting add-on of any ICE. Apart from the flexibility in the installation, the EWP permits the precise control of the engine temperature in any operating condition through the variation of the coolant flow. Precise cooling optimizes the design of otherwise oversized coolant passages. The pump of the WHRS is the pump of the coolant. Both the pump and the expander of the WHRS are connected to the electric ES through electric MU or GU. The motor/generator units on the pump and expander axes allow the full decoupling of the pump and expander operation for the engine operation.

Ethylene (or propylene) glycol based water solutions are considered as the working fluid, as these solutions are necessary for operation in environments where the temperature in the heat transfer fluid can drop below 0 ºC. Specific heat capacity, viscosity and specific weight of the water and ethylene glycol solution vary significantly with the percent of ethylene glycol. At ambient pressure, addition of ethylene glycol may lower the freezing point from 0ºC to -7.9 ºC (20% by volume) to -36.8 ºC (50% by volume), while it may increase the boiling point from 100 ºC to 102.2 ºC (20% by volume) to 107.2 ºC (50% by volume). While the dynamic viscosity and the specific gravity of ethylene glycol based water solutions significantly increase with the % by volume of ethylene glycol, the specific heat capacity reduces. The present glycol content is not optimized for the WHRS operation.

6. Preliminary Computational Results

The present work provides a very preliminary computational assessment of the advantages of an integrated WHRS with by-pass of the expander and condenser also having turbocharger, expander, pump all connected through electric MGU to the electric ES that is also connected to the wheels through the KERS MGU.

Virtual engine and vehicle models were developed by using the GT-SUITE software [20-21]. GT-SUITE is one of the industry-leading simulation tools with capabilities and libraries aimed at a wide variety of applications in automotive engineering permitting from fast concept design to detailed system or sub-system/component analyses and design optimization. The multi-physic approach is based on libraries for flow of any fluid, gas or liquid or mixture, acoustic, both non-linear and linear, thermal, including all types of heat transfer, mechanical, either kinematics, multi-body dynamics, frequency domain, electric and electromagnetic, describing circuits and electromechanical devices, chemistry, describing chemical kinetics, controls, with signal processing. Built-in facilities permit easy integration with 3D CFD as well as 3D FEM, for detailed fluid dynamic, thermal or structural analyses. GT-SUITE is used by the most part of the OEMs and their suppliers, plus universities and research centers. Almost 800 of the many papers published reporting on the GT-SUITE model development; validation and application are listed in [21].

The vehicle "system of systems" model comprises the oil system, the coolant system, the engine (gas) system, and the engine (metal) system, the radiator, the hybrid drive train, the energy store (ES) and the electronic control unit (ECU). Every component is detailed to permit the optimization of the subsystem as well as of the system. The engine friction is modelled as a function of temperature and load and speed through empirical maps. Oil and coolant pumps are electrical. The engine is turbocharged with air cooler. The engine is gasoline fueled, directly injected, with combustion controlled by a spark in a jet ignition pre-chamber. Downstream of the turbocharger, the exhaust line includes the catalytic converter and the muffler. This specific engine configuration has no exhaust gas recirculation (EGR). Compressor and turbine of the turbocharger are connected to a MGU. The WHRS model comprises a pre-heater (the engine coolant passages), a boiler/super heater on the engine exhaust, an expander, a condenser and a pump. The pump is the engine pump electrically driven. A recuperator is used to improve the thermal efficiency of the cycle, usually low due to the close temperature levels of cold and hot reservoirs. Other waste heat may be recovered, but this translates in additional heat exchangers to those already existing in a more complicated WHRS layout. If the WHRS is integrated with the engine, the thermal inertia is reduced, only the more precious and easy to be recovered of the waste heat is used. The WHRS circuit has the expander and condenser bypassed for a much quicker warm up before starting to recover energy in the expander. The compressed air cooler is not included in the WHRS as this translates in more complications and increased thermal inertia limiting the actual benefits during the cold start transients. Oil cooling is similarly not included in the WHRS.

The general layout is substantially simplified vs. the BMW Turbo-steamer layout. The WHRS pump is now the pump that provides the energy needed for the circulation of the single coolant over the engine and the integrated WHRS. It replaces the traditional coolant pump. Similarly, the radiator and the condenser are now replaced by a single unit performing the condensing of the steam. The pump and expander of the WHRS are driven by motors or are driving a generator connected to the ES of the vehicle.

A MGU is also connected to the driveline and the ES to recover the vehicle kinetic energy and boost the engine output with the recovered energy (electrical KERS). The much quicker warm-up obtained by using the integrated WHRS system by-passing turbine and condenser is needed when using the KERS. The KERS may indeed reduce the amount of fuel energy needed by simply using the KERS boost to accelerate the vehicle after a deceleration rather than the engine. Integrated with start/stop, the engine is shut down, or otherwise idling, when energy above a threshold in the ES is available to cover the driving requirements. However, this drastically increases the warm-up time.

A hybrid vehicle powered by a naturally aspirated gasoline engine is certainly the best solution presently available on the market in terms of fuel economy covering driving cycles. Unfortunately, this fuel efficiency result is obtained by using complex buffering strategies of the ICE where the use of the electric motor connected to the traction battery and the ICE is optimized for the specific task. Therefore, moving far from the certification test, the actual benefits of the hybridization drastically reduce. As the driver usually has no opportunity to predict the road conditions ahead, a simple charging and discharging strategy is used for the re-use of the recovered energy in this work. No complex buffering strategy is therefore considered in the present work, but the recovered energy in one braking is immediately reused in the following acceleration.

Only preliminary results are provided here, comparing the baseline configuration that uses a traditional power train - no KERS - and a traditional engine - no WHRS, with the configuration featuring the engine redesigned for the integrated WHRS and the KERS.

Simulations have been performed for a Sport Utility Vehicle (SUV) equipped with a turbocharged 1.6 liter in-line four gasoline direct injection jet ignition engine covering the cold start NEDC. Bore and stroke are 80x80 mm, connecting rod length is 130 mm and the compression ratio is 10:1. The drag coefficient is 0.3 with a reference frontal area of 2 m^2. The baseline configuration with no WHRS and no KERS has weight 1650 kg. A weight penalty of 25 kg is considered with either the KERS or the WHRS, 50 Kg with both systems fitted. Fuel is indolene of density 750 kg/m^3, lower heating value 43.95 MJ/kg, carbon and hydrogen atoms per molecule 7.93 and 14.8 respectively.

In the baseline configuration, the temperatures of metal, media and gases show the warm-up is incomplete at the end of the cycle. The metal temperatures are warming all over the cycle, with a reducing rate during the ECE-15 segments, and then an increasing rate when the EUDC starts. Fully warmed up conditions of the metal are not achieved before the end of the cycle. The warm-up of the coolant is never completed during the cycle. The oil temperature is reducing during the EUDC segment because the oil starts to be cooled during the highway driving. The energy available at the exit of the compressor is minimal, while the energy available after the turbine is increasing over the cycle and becomes significant over the EUDC, the extra urban portion of the NEDC. At the entry of the exhaust manifold, the energy available is much larger than at the exit of the turbine. The thermal inertia of the baseline engine configuration is by far excessive to permit a fast warm up and a significant recovery of the energy in the coolant and the exhaust gases. A complete redesign of the engine for the integrated WHRS is therefore needed to deliver first a very fast warm up, and then the recovery of the waste energy.

In addition to the baseline engine without KERS, simulations have therefore been performed by replacing the engine with an engine specifically developed with an integrated WHRS having the quicker warm up ability, and adding the KERS. In the modified configuration, a reduction of the thermal inertia – basically mass of metal, coolant and oil - translates in a much quicker warm-up. The operation of the coolant pump electric is one enabler of a better design and further accelerates the warm-up as the coolant flow may be freely tuned as a function of not only engine speed, but also engine load and coolant and metal temperatures. A further speed up of the warm-up is achieved by using part of the exhaust energy downstream of the turbocharger turbine. With the integrated WHRS and without KERS, the warm-up is completed during the third ECE-15 segment. With the KERS, the warm-up is delayed towards the end of the EUDC. With the KERS, there is a consistent fuel energy saving during the ECE-15 segments.

Fuel flow rate results are provided in Fig. 2, while the fuel economy results are given in Fig. 3.

Fig. 2(a) presents the NEDC schedule as a reference. This velocity schedule determines the power supply from the engine and the KERS as well as the power dissipated in the friction brakes or recovered by the KERS.

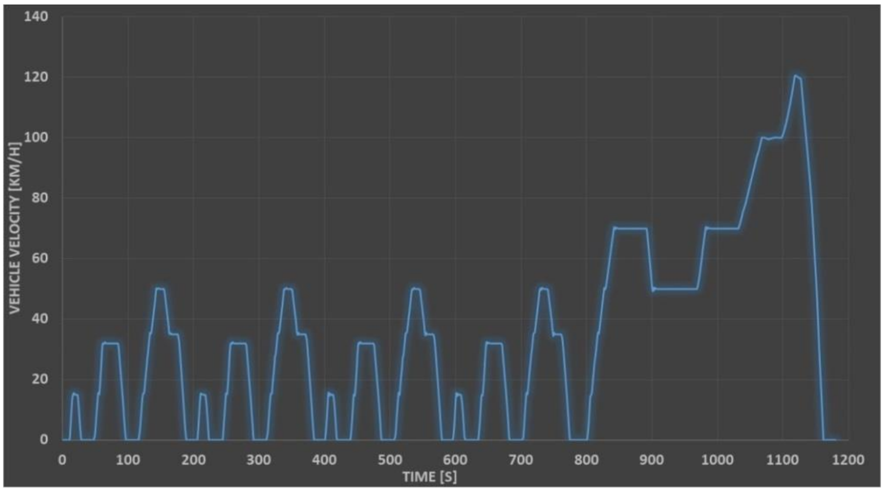
Fig. 2(b) presents the splitting of the power provided by the internal combustion engine (ICE) and the KERS when the power train is fitted with the device used to recover the kinetic energy. While more complicated strategies are possible to deliver apparently better fuel economies in the certification cycles, the adopted strategy uses the energy recovered in a braking event in the acceleration event that immediately follows the braking event. Opposite to present hybrid and electric vehicles, the KERS therefore stores more energy than the energy it uses during the NEDC. This image permits to understand when the engine is not needed in case there is a KERS.

Fig. 2(c) presents the fuel flow rates needed by the engine to deliver this velocity schedule for the baseline (starting point) configuration that has no WHRS and no KERS, for the engine modified to integrate the WHRS but no KERS fitted to the power train, and finally for the configuration with the novel engine with the integrated WHRS and the KERS fitted to the powertrain. The only difference that may be appreciated in this graph is when the ICE is turned off, as the differences in between the ICE efficiency with or without the integrated WHRS may be hardly detected during the load changes.

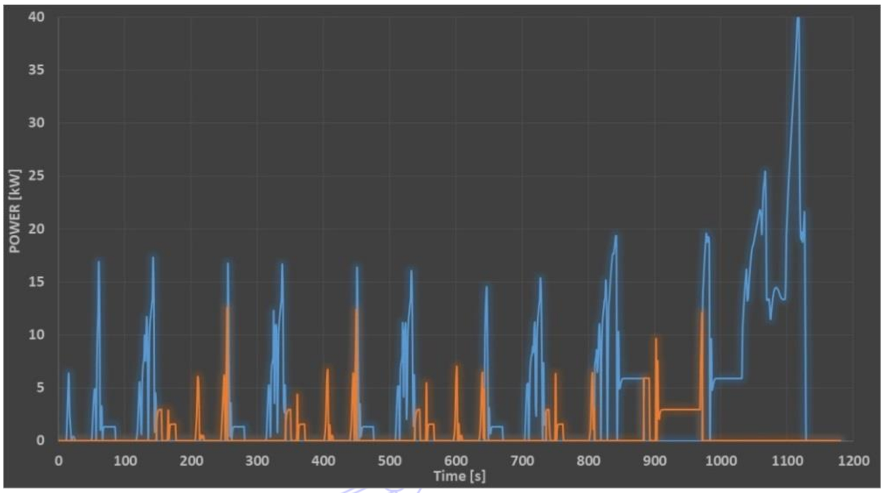
To be noted, the case “WHRS” differs from the “baseline” case only for the quicker warm-up translating in reduced friction losses and for the slightly better fuel conversion efficiencies after warm-up working with the higher temperatures of metal and coolant thanks to the EWP. The expander power supply to the ES is not accounted for in the fuel economy computation.

In the case “WHRS+KERS” the discharge strategy of the ES is the one shown in Fig. 2(b). The ES is replenished by the KERS during regenerative braking and by the generator connected to the expander of the WHRS after the engine is fully warmed up. During the NEDC, the WHRS mostly produces energy during the final extra urban portion of the cycle. Additionally, the braking event where more energy is produced by the KERS is the final braking from 120 km/h to rest at the end of the NEDC. The expander power supply to the ES during the most part of the extra-urban sector and the KERS power supply to the ES during the final deceleration are not accounted for in the fuel economy computation.

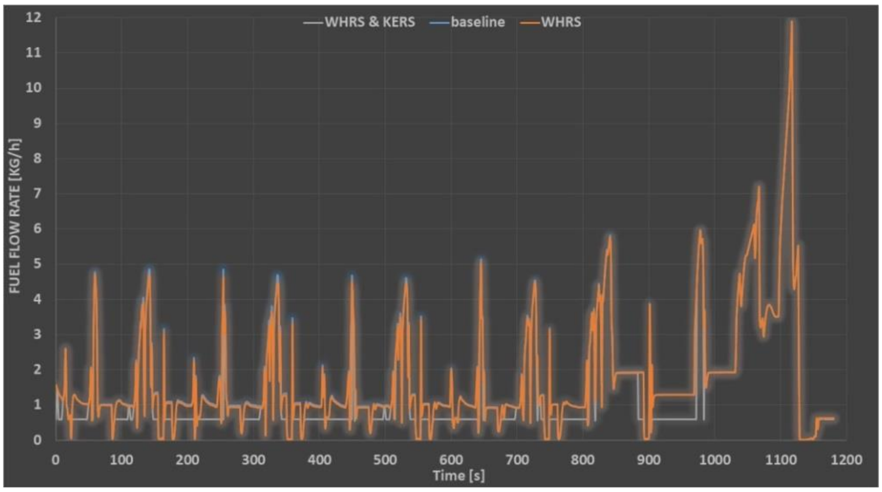
Figure 3 presents the preliminary fuel economy results of the vehicle with the baseline engine and a traditional power train configuration, with the modified engine featuring the proposed integrated WHRS, and for the modified engine featuring the proposed integrated WHRS plus a driveline KERS. In the present energy recovery strategy, Fig. 2(b), the ES is first recharged and then replenished. A significant amount of energy recovered by the KERS and the WHRS is thus left unutilized at the end of the cycle. By adopting a more complex use of the energy delivered to the ES, the fuel economy advantages may be further improved. The advantages of the proposed solution are underrated, as the ES has extra energy from both the WHRS and the KERS at the end of the cycle.



(a) NEDC velocity schedule



(b) Power provided by ICE (blue) and KERS (red) for the WHRS+KERS configuration



(c) Fuel flow rate for the baseline (black), WHRS (green) and WHRS+KERS (blue) configurations

Fig. 2 Preliminary fuel flow rate results for the baseline configuration, the engine modified for the WHRS and the modified engine plus a KERS

The baseline configuration has a fuel economy of 9.41 liters/100 km over the city driving (UDC), and 5.46 liters/100 km over the extra urban driving (EUDC). The combined fuel economy figure NEDC is 6.93 liters/100 km. The novel integrated

WHRS delivers a much quicker warm up that is completed during the first of the four portions of the city driving. The system also permits the recovery of the waste energy that becomes possible after the warm-up is completed and generally increases with the load and the speed. The recovery of the waste energy is only possible during the EUDC. The ES is charged by the engine only during the EUDC. The friction losses reduce during the first segments of the UDC.

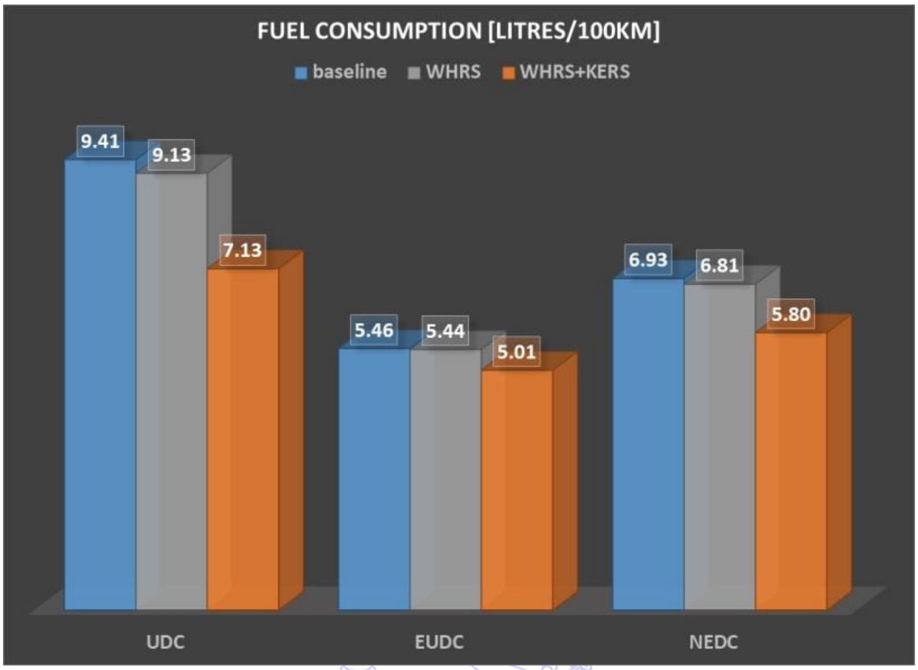


Fig. 3 Preliminary fuel economy results

With the WHRS only, the fuel economy improves to 9.13 liters/100 km and 5.44 liters/100 km respectively on the city (UDC) and extra urban (EUDC) driving. The combined fuel economy figure NEDC is then 6.80 liters/100 km. The advantage of adopting a WHRS is a minimal 1.7%.

By further adding the KERS, the fuel economy improves to 7.13 liters/100 km and 4.99 liters/100 km respectively in the city (UDC) and extra urban (EUDC) driving. The combined fuel economy figure NEDC is then 5.80 liters/100 km. The advantage of adopting a WHRS with a KERS is a more consistent 15%.

With the KERS, the warm up is made slower than without the KERS, because the thermal engine is not always used. The major advantage is the use of the recovered braking energy during the city driving. The KERS is simply operated by reusing the recovered energy immediately after a deceleration charge of the ES in the following acceleration and cruising. The engine has simply the fuel cut-off when no thermal power supply is requested. More complex buffering strategies are not investigated. The start/stop option is similarly not investigated. Starting from a partially charged ES, the final energy is much larger than the initial energy. This is not accounted in the simulations. With the proposed simple use of the KERS, the kinetic energy recovered in the final sharp braking event adds to the charge of the ES. Similarly, not accounted is the WHRS turbine charging the ES during the high load points of the EUDC.

7. Discussion

The results, despite subjected to the many uncertainties of the complex simulation involving components not exactly off-the-shelf and the far-from-optimal control, are certainly encouraging. They are suggesting the opportunity to achieve more than 15% better than today’s fuel economies under real driving conditions, as more complex buffering strategies delivering better fuel economies over the NEDC building on the kinetic energy recovered at the end of the cycle are very difficult to achieve in practice. The NEDC is indeed quite unrealistic, with the last sharp braking from 120 km/h to parked never experienced by anyone living in Europe.

Certainly, the relative position of turbocharger turbine and WHRS heat exchanger is subject to discussion and it is similarly to the location of the catalytic converter not considered in the present analysis. As the turbocharger is connected to the ES via a motor/generator, there is no need to balance the compressor work with the turbine work. The motor/generator on the turbocharger axis permits indeed to fully decouple the compressor demand from the harvesting of exhaust energy in the turbine. Therefore, making the WHRS boiler/super heater the exhaust manifold is certainly worth investigating. The WHRS boiler/super heater may be also placed in the exhaust manifold upstream of the turbine to recover much more energy rather than downstream of the turbine.

The proposed WHRS plus KERS concept obviously also applies to naturally aspirated engines where the layout is made simpler by the absence of the turbocharger and the air cooler. In a naturally aspirated engine, not having a turbine, the energy available in the exhaust is greater.

The present modelling results do not include the presence of a chemically active catalytic converter. There is no model for pollutants' emissions. In a turbocharged gasoline engine, the catalytic converter is usually placed downstream of the turbine. It may be split into two components for packaging. Some manufacturer is also using a pre-catalyst close to the engine upstream of the turbine and then a larger second catalyst downstream of the turbine, with the pre-catalyst helping with the cold start but posing some issues with the operation of the turbine. It is worth mentioning the temperatures after the catalyst may be larger than the temperatures before, but the pressure will be certainly reduced. The proper design of the after-treatment, turbocharger and waste heat recovery in the turbocharged gasoline engine lean burn considered here definitively needs further studies.

The condenser is the weaker part of the proposed design. Air cooled condensers do not need water to condense the process fluid. The exhaust steam from the turbine flows through the tube bundles of an air-cooled condenser being condensed using the forced air flow. However, it may be argued that this translates in a significantly large volume, weight and inertia, and automotive condensers are presently unavailable off-the-shelf.

We have proposed an integrated WHRS for a turbocharged engine incorporated in a hybrid electric driveline. The WHRS is made up of the coolant engine passages, and then a heat exchanger on the exhaust, plus an expander, condenser and pump. The expander and condenser may be by-passed during cold start. The expander and pump are connected to the energy storage through motor/generator units. The EWP permits precise cooling on demand. The bypass of the expander and condenser during cold start and the proper operation of the electric pump delivers a much quicker warm-up. After warming up, the expander charges the energy storage, thus improving the fuel energy conversion efficiency.

Further research and development is certainly needed to improve the solution up to a level suitable for mass deployment, this innovation may bring significant benefits in terms of fuel consumption and emission both during cold start driving cycles than highway (steady) driving. In the preliminary simulations, the combined fuel economy figure over the NEDC is reduced from the 6.93 liters/100 km of the baseline configuration to 5.80 liters/100 km. This 15% better fuel economy does not include the energy stored in the ES during the last braking event closing the unrealistic NEDC driving schedule, and similarly the energy produced by the WHRS during the last part of the NEDC and transferred to the ES. However, similarly neglected is the energy consumed by the EWP.

The mechanical energy available in the WHRS expander shaft is converted into electric energy by the generator and it is then converted into chemical energy in the ES (battery). Before being used on the wheels, this chemical energy must be transformed back into electrical and then finally into mechanical energy by the KERS motor. Therefore, it is not correct to sum the WHRS expander power to the crankshaft power as total mechanical power. The total fuel conversion efficiency computed as the ratio of these two powers to the fuel flow power is misleading. Also, considering the goal of this paper is to discuss the benefit of adopting an integrated WHRS during cold start driving cycles such as the NEDC, the steady state total fuel conversion efficiency maps of the engine vs. BMEP and speed are not shown here.

8. Conclusions

The major advantage of the integrated WHRS is the opportunity to achieve a much quicker warm-up by-passing the expander and condenser and using the exhaust waste heat to warm-up the coolant. Additionally, thanks to the engine redesign with the coolant flow controlled by an EWP, the more uniform, higher coolant and metal temperatures translate in reduced heat losses, and hence better engine fuel conversion efficiency, in addition to a further reduced thermal inertia.

With a KERS, the addition of a WHRS that may be operated with expander and condenser by passing is necessary to avoid warm-up times that may exceed the length of the cycle. The integrated WHRS power generation has become significant only in the last portion of the NEDC cycle where the engine speeds and loads become important. While during prolonged highway driving the benefits of the integrated WHRS may be substantial, the cold start city driving does not benefit from WHRS.

It is therefore of paramount importance to better define the cycles our cars must be optimized for, as there is a growing divergence in between real driving conditions and certification tests. A traditional WHRS does not produce any benefit over the cold start NEDC. When a KERS is fitted, the addition of a traditional WHRS is even more negative. While the integrated WHRS produces some advantages over the cold start NEDC, the waste heat recovered itself is still minimal to promote a WHRS vs. a EGHR coupled to an EWP. A more extensive operation of the car is therefore needed to fully benefit from the integrated WHRS.

Abbreviations

E-KERS	Electric KERS	ICE	Internal Combustion Engine
ES	Energy Store	MGU	Motor-Generator Unit
EWP	Electric Water Pump	MGU-H	Motor-Generator Unit on the Turbocharger Shaft
EGHR	Exhaust Gas Heat Recovery	MGU-K	Motor-Generator Unit On The Driveline
ECU	Electronic Control Unit	MU	Motor Unit
EGR	Exhaust Gas Recirculation	NEDC	New European Driving Cycle
ECE-15	Economic Commission for Europe - 15 Urban Drive Cycle	UDC	Urban Driving Cycle
EUDC	Extra Urban Driving Cycle	WOT	Wide Open Throttle
GU	Generator Unit	WHRS	Waste Heat Recovery Systems
KERS	Kinetic Energy Recovery Systems		

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