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Micro Steam Turbines for Hybrid Power Source Vehicles

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Abstract

The paper describes a new hybrid power system for vehicles consisting in an Internal Combustion Engine (ICE) plus a micro steam turbine (MST) that supplies energy to an electric motor. The result of this hybridization is a reduction in fuel consumption and an improvement in performance efficiency. The micro steam turbine unit uses the released thermal energy from the ICE to generate water vapor flow, which is accelerated in a convergent nozzle to increase the kinetic energy, carrying the accelerated flow to the micro steam turbine. A simulation analysis shows that the hybrid engine increases the supplied power by 3.4% for a gasoline internal combustion engine vehicle, and by 4.1% for a diesel. Power gain ratio of a micro steam turbine set regarding lithium battery system is 2.0% for gasoline ICE and 1.8% for diesel. Regarding the cost, a MST unit is 3.2 times more expensive than a lithium battery if we compute initial investment; however, the normalized price over the lifespan is similar, 34.6 €/kWh·year for the battery power system, and 35.3 €/kWh·year for the micro steam turbine set.

Keywords: Internal Combustion Engine; Micro steam turbine; Vehicle Engine Hybridization; Thermal Energy Recovery; Improvement of the Coefficient of Performance

INTRODUCTION

Hybrid power sources for today's automobiles mainly consist of an internal combustion engine (ICE) and an electric motor, which is powered by batteries or fuel cells [1–2]. Among these two options, the one with batteries is the most representative [3]. Other alternatives, like batteries and supercapacitors or batteries and fuel cells, are less frequent, representing a low percentage of the hybrid vehicle fleet market. In conventional hybrid power vehicles equipped with batteries, two configurations appear: the one where the batteries are charged from a vehicle's built-in electric generator, and the other where the battery is recharged from the grid. There is a controversy about which option is better since both have advantages and drawbacks [4–6].

Battery hybrid vehicles suffer from a low extra power due to the reduced size and power of the battery [7–8], whose main goal is supplying energy to the electric motor to help the combustion engine in the acceleration process and uphill road, or reduce engine idling when the vehicle is stopped. Together, these features result in better fuel economy without sacrificing performance [9].

Many works are devoted to study, characterize and analyze the behavior of a battery hybrid vehicle, comparing its performance to the conventional ICE cars, and showing the benefits of using batteries to reduce fuel consumption, which reduces environmental impact [10–11]. The alternative of using fuel cell instead of batteries is more expensive

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and increases maintenance due to the existing problems of fowling and flooding in the fuel cell membrane [12–14].

A vehicle should be equipped with a powerful electric generator to supply the required energy demand from the electric motor to avoid external dependence of battery recharging or hydrogen supply for the fuel cell system [15–17]. This configuration, however, is inefficient since it requires transforming the mechanical energy from the ICE to electric current, thus reducing the efficiency of the overall energy conversion process.

An already studied option to generate electricity in hybrid cars derives from using micro gas and steam turbines [18–21]. These systems operate with compressed natural gas (CNG) or water vapor as primary fuel, reducing the dependence on diesel or gasoline and lowering the fuel consumption.

In this work, however, we propose to use the released thermal energy from the ICE cooling system to generate water vapor for a micro steam turbine, which moves an electric generator to produce the electricity required by the electric motor. The micro steam turbine operates in a closed thermodynamic cycle at the appropriate pressures and temperatures. The new configuration represents a more complex design but produces extra power at low energy cost, increasing the global efficiency of the vehicle power system, lowering fuel consumption, and reducing environmental impact.

SYSTEM DESIGN

Steam turbine operates similarly to conventional units [22], with the only system size difference. A schematic view of the proposed power system layout is shown in Figure 1.

The terms Q_{ext}, q_s, and q_f represent the external heat, and vapor and fluid flow.

OPERATIONAL MODE

Looking at Figure 1, the operational mode is as follows:

- Released thermal energy from the combustion process at the internal combustion engine is dissipated at the cooling radiator
- Thermal energy is transferred from the cooling radiator to a heat exchanger where a heat fluid carrier, currently water, circulates in a closed loop between the heat exchanger and the boiler
- Energy from the heat fluid carrier is transferred to water at the boiler, thus increasing water temperature to its maximum compatible level with thermodynamic conditions. Water from the heat exchanger circuit and the boiler do not mix up since they circulate inside and outside the heat exchanger section located in the boiler
- Water from the micro steam turbine circuit is heated up until evaporated
- Water vapor is carried to the micro steam turbine producing mechanical movement, which is transferred to the electric generator
- Low enthalpy water vapor exits the turbine and enters a condenser to be transformed into liquid phase
- Liquid water is collected from the condenser and stored in a water tank
- Liquid water from the water tank is pumped back to the boiler using a mechanical pump, closing the circuit
- The current generated at the electric generator powers the electric motor, which is connected to a power split device
- The internal combustion engine is connected to the power split device through a coupling system
- The split device is commanded by a control system, which decides the power source to supply energy to the drivetrain, ICE, electric motor, or both
- The control system follows a manufacturer set-up protocol
- The protocol is based on standard driving patterns and conditions, but can be adapted by the manufacturer to the specific characteristics of the vehicle; therefore, the protocol is unique for every vehicle brand and model

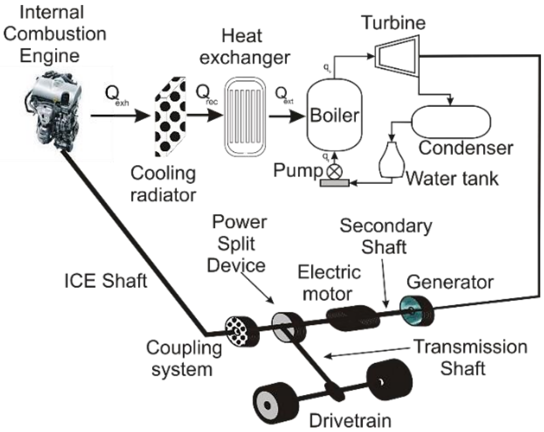

Figure 1. Layout of the vehicle power system.

CONTROL SYSTEM PROTOCOL

Based on previous studies, the control system uses a power management strategy to minimize fuel consumption and optimize vehicle performance [23–25]. The strategy depends on the powertrain configuration [26–27], which is characteristic of every car manufacturer, and on the vehicle power requirements, which depend on the driver's pattern and driving conditions [28–30].

A standardization process in control system protocol from power management strategy is complex because of the many intervening variables, acceleration, speed, drag and rolling coefficient, road slope, route distance, traveling time, traffic congestion, etc. Nevertheless, we can develop a specific protocol based on defined premises, which apply to almost any case. To do so, we consider the power ratio between ICE and micro steam turbine as the reference parameter for the protocol.

In current hybrid electric vehicles (HEVs), equipped with an electric motor powered by a lithium battery, the electric motor is used to boost the vehicle when the battery state of charge (SOC) exceeds a setup threshold to preserve the battery state of health (SOH) [31], fulfills eco-driving criteria [32], or matches rules optimization, multi-computing rates, pattern recognition, prediction/estimation, and intelligent transportation systems (ITS) [33]. In many of the above situations, the vehicle power requirement threshold is variable because of the dependence on driving and environmental conditions as well as vehicle characteristics [34], which leaves the connection process of the electric motor subject to the criteria of the designer of the hybrid electric vehicle, whose main worry is the fuel consumption lowering [35–36].

In a hybrid ICE/MST system, since the micro steam turbine supplies a limited output power, which depends on the MST size, with no energy reservoir available, the application criterion of electric motor engagement should change. On the other hand, the MST system performance depends on the ICE operation; the greater the power demand of the internal combustion engine and the consumption of the vehicle, the greater the need to dissipate thermal energy, so the cooling water flow will increase, resulting in greater power generated in the micro steam turbine system.

According to this statement, we set up the micro steam turbine system state as always engaged, supplying power up to its limit; nevertheless, to preserve MST durability, we establish 90% of maximum output power as the operational threshold. The flowchart of Figure 2 shows the control system protocol.

The condition MST OFF does not mean that the micro steam turbine system is deactivated; the control system only disengages the MST from the vehicle power train, but the micro steam turbine unit continues supplying power to the ancillary equipment of the vehicle and auxiliary elements of the propulsion system. This configuration guarantees the internal combustion engine operation at high efficiency while ensuring the energy supply to ancillary equipment and auxiliary services.

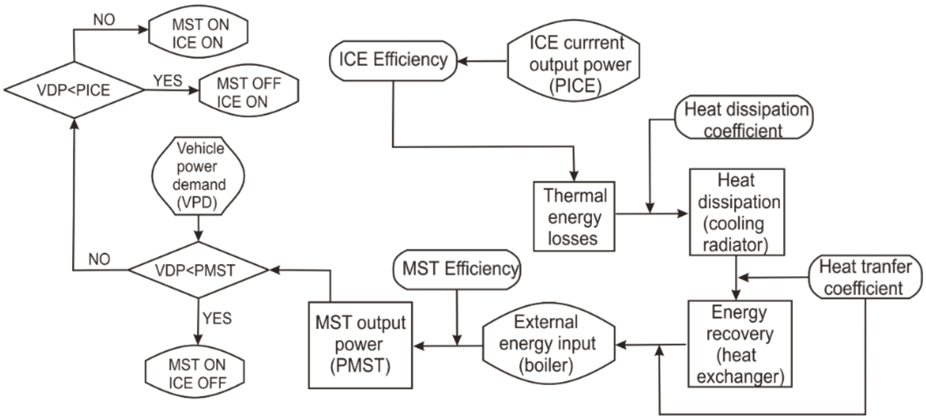

Figure 2. Control system protocol flowchart.

Table 1. Characteristics of diesel and gasoline internal combustion engine.

ICE type (fuel)	ICE efficiency	Fuel density (kg/m^3)	Fuel combustion power (MJ/kg)	Turning speed range (rpm)
Diesel	0.3 [37]	860–900 [38]	37.1 [38]	300–5000 [39]
Gasoline	0.25 [40–41]	710–770 [42]	46.7 [43]	800-6000 [44]

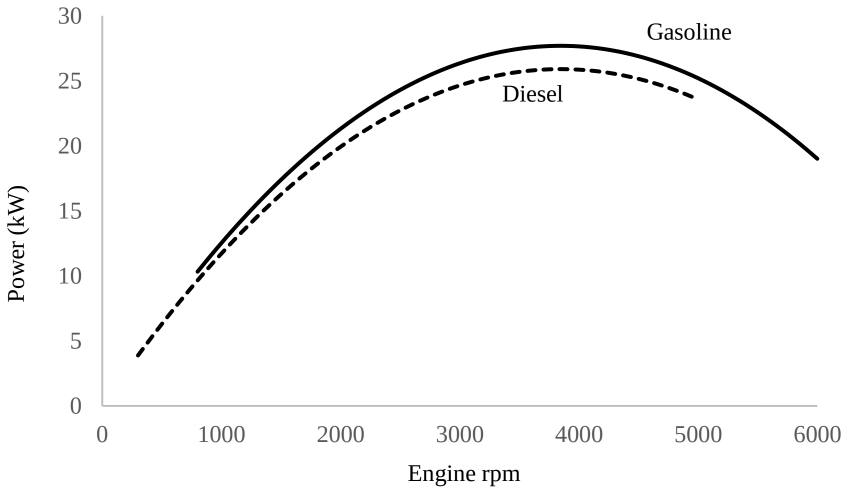

Figure 3. Thermal energy release at the cooling radiator of the ICE.

SIMULATION

To run a simulation, we apply standard driving conditions to a regular car equipped with a conventional internal combustion engine and a low power micro steam turbine unit.

To determine thermal energy released from the ICE cooling system, we apply the following expression:

$$\xi_{th} = L_f \eta_{eng} \omega G \tag{1}$$

L_f accounts for the specific fuel combustion power, η_{eng} is the ICE efficiency, ω is the engine turning speed, in rpm, and G is the fuel consumption per cylinder stroke.

We consider two ICE types, diesel and gasoline. Table 1 summarizes the main characteristics of the two types regarding the simulation study.

Applying equation 1 to data in Table 1, we obtain the thermal energy release at the cooling radiator of the ICE (Figure 3).

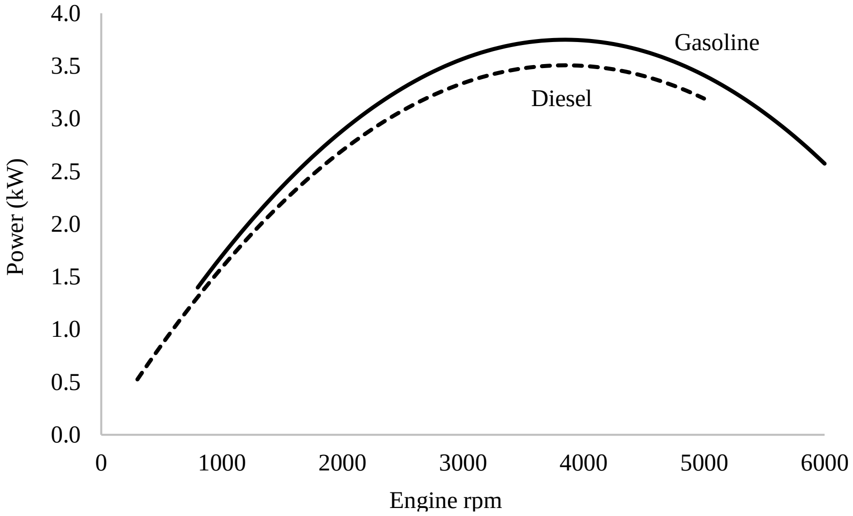

Figure 4. Micro steam turbine system output power.

We notice that gasoline ICE releases more energy than diesel, although the difference is not important, less than 7%.

We also notice that thermal energy release depends on the engine turning speed, increasing to a maximum at 3800 rpm, then decreasing.

Considering a heat transfer coefficient of 95% at the heat exchanger and boiler, which is a current value, and applying a micro steam turbine system efficiency of 15% [45], we obtain the effective output power from the MST unit as a function of the ICE regime (Figure 4).

Averaging over the entire range of ICE turning speed, we obtain the following values for the diesel and gasoline engines.

$$\dot{W} = \left| \begin{array}{l} 2.712\,kW \quad (diesel) \\ 3.105\,kW \ (gasoline) \end{array} \right. \tag{2}$$

Now, comparing with current power values from lithium batteries for hybrid electric vehicles, between 0.8 kW and 1.5 kW, we observe that the micro steam turbine generates between 2.7 (gasoline) and 2.4 (diesel) more energy than a battery, on average; therefore, the implementation of a MST unit coupled to the ICE cooling system results in an increase of the available energy from the auxiliary power source.

In terms of relative gain, the MST unit increases the output power of the hybrid system by 3.4% for the gasoline engine and 4.1% for the diesel, on average. On the other hand, if we calculate the relative gain of an ICE/MST system regarding an HEV with a lithium battery, we obtain an increase of 2.0% for the gasoline engine and 1.8% for the diesel, on average.

Nevertheless, the micro steam turbine system does not show the same power gain evolution as a hybrid power system equipped with a lithium battery (Figure 5). We observe that the gasoline engine maintains a constant power gain ratio with positive values over the entire engine turning speed range; however, for the diesel engine, at low turning speed regime, below 800 rpm, the ICE/MST hybrid system penalizes the performance reducing the power gain by 2%, on average.

Now, summarizing the comparative analysis of the two hybrid power source systems, ICE plus lithium battery, and ICE/MST, it results (Table 2):

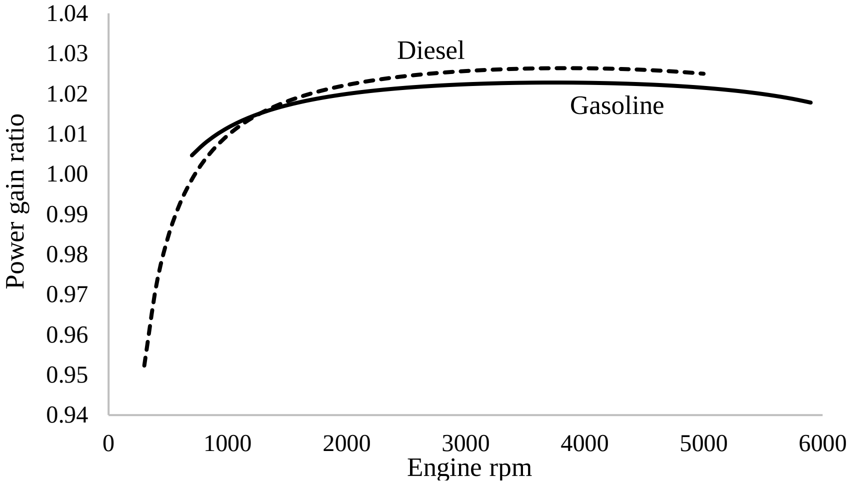

Figure 5. Power gain ratio of ICE/MST to ICE-battery system.

Table 2. Comparative results of hybrid power sources for vehicles (average values).

	ICE + Li-battery		**ICE + MST**	
ICE type →	***Gasoline***	***Diesel***	***Gasoline***	***Diesel***
Output power (kW)	92.951	67.979	94.857	69.491
Power gain (%)	---	---	3.4	4.1
Power gain ratio	---	---	2.0	1.8

DESIGN AND ECONOMIC ANALYSIS

Micro steam turbine implementation in a hybrid internal combustion engine power source suffers from disadvantages regarding a conventional hybrid model with a lithium battery. Among them, we can mention a more complex design derived from the many elements the MST unit includes and a higher investment and cost maintenance. Another problem is the energy requirement to operate the MST system since the mechanical pump requires electric energy to work. The presence of mobile parts also increases the maintenance and operation costs, which reduce the global performance of the system.

In economic terms, the profitability of the new system depends on its lifespan. For short operational times, the system is not economically profitable; however, for long life operating times, economic profitability is guaranteed.

Comparing prices for micro steam turbine and lithium battery of the same energy capacity, we observe the battery is less expensive, 277 €/kWh (301 US$/kWh) (25000 Rs/kWh) [46] than the micro steam turbine 883 €/kWh (960 US$/kWh) (79700 Rs/kWh) [47-48]. However, the durability of the MST unit is longer, which compensates for the extra cost; normalizing for 25 years lifespan, we obtain:

$$C = \left| \begin{array}{ll} 34.6\ \text{€} / kWh \cdot year & (Battery) \\ 35.3\ \text{€} / kWh \cdot year & (Micro\ Steam\ Turbine) \end{array} \right. \qquad (3)$$

The above results show that lithium battery and MST unit have the same normalized price if we operate over the system lifespan.

CONCLUSIONS

Micro steam turbine system is a feasible solution to generate electricity in hybrid power systems for internal combustion engine vehicles.

Micro steam turbine operates under thermal principles using heat recovery from the internal combustion engine cooling circuit.

For standard conditions, a micro steam turbine unit generates 2.7 times more energy than a lithium battery for a gasoline internal combustion engine and 2.4 times more for diesel.

The average power increase using a micro steam turbine is 3.1 kW for gasoline ICE and 2.7 kW for diesel.

The power gain ratio from micro steam turbine to lithium battery auxiliary power source is 3.4% for gasoline and 4.1% for diesel, on average.

Micro steam turbine set requires a higher investment, 3.2 times more, but it compensates due to its longer lifespan; the normalized cost is similar, 34.6 €/kWh·year for the battery, and 35.3 €/kWh·year for the micro steam turbine.

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