Study on performance of an innovative power system for hybrid propulsion consisting in a gas turbine with heat exchanger and steam turbine

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Abstract. Hybrid electric vehicles are currently considered a viable solution for fossil fuel saving and pollutant emissions reduction in transportation sector. The typical configuration of a hybrid electric propulsion system contains a reciprocating internal combustion engine – gasoline or diesel. Aiming to increase performance and to reduce pollution in road transport, a hybrid electric propulsion system based on a micro gas and steam turbine system operating with compressed natural gas is proposed in the paper. The micro gas turbine has a recuperative heat exchanger and the steam cycle has one pressure level. The study analysed the performance of the proposed system as a function of gas turbine engine pressure ratio and temperature difference of the gas turbine engine heat exchanger. Results indicate that, at equal power, the analysed system is more performant than internal combustion engines currently used in hybrid electric propulsion, so they could represent a viable solution in this field.

1. Introduction

Fossil fuels shortage and concern for clean power generation solutions in the propulsion systems sector have led to a growing interest for the electric traction. Excluding the vehicles with continuous connection to the power network (such as trolleys and trams), which require specific infrastructure facilities, all electric vehicles incorporate some sort of energy storage systems. In the case of pure electric vehicles, the most stringent problem is to ensure the drive range need. As indicated in [1], identifying of the range needs requires studies using individual real travel data, which also indicates the adequate locations of charging stations. Besides the drive range problem, pure electric vehicles are not cost competitive [2], so they need substantial subsidies support to be financially attractive [3]. The drive range is significantly extended in the case of hybrid electric vehicles (HEV), which typically combine an electric motor and an internal combustion engine (ICE).

For both pure electric and hybrid electric technology the mobility range improvement and vehicle cost reduction are inherently related to the development of the electric energy storage; presently, the supercapacitors are the most promising energy storage devices due to a short charging time and long lifespan [4]. Obviously, the energy management is also very important. Accordingly, management strategies for maximum braking energy recovery were studied [5, 6], while optimum energy distribution between the electric source and ICE was analysed in [7].

In addition to extending the drive range, the performance improvement represents a major concern in the field of hybrid electric vehicles. Aiming to higher performance, several solutions have been
studied lately as alternative to ICE for integration in hybrid electric vehicles. Fuel cell appears to be one promising solution. A hybrid fuel cell electric vehicle has the advantage that uses only the electric motor. The experimental study on a hybrid propulsion system consisting in a 90 kW proton exchange membrane fuel cell and a supercapacitor, performed in [8], indicates impressive performance such as a drive range of 435 km and a maximum speed of 158 km/h. It was shown that performance can be improved by using a lithium-ion battery together with a supercapacitor [9]; in this case, the drive range extended to 545 km and the maximum speed was 161 km/h.

Gas turbine and combined cycle units based on gas turbine also represent an alternative to ICE, not only in conventional approach [10], but also for hybrid propulsion systems. The use of the gas turbine for waste heat recovery from ICE exhaust gases of a hybrid propulsion system improves fuel economy with more than 5% [11]. It was also investigated the use of the gas turbine as range extender of a hybrid vehicle – in simple cycle [12] or in combined cycle [13, 14]. Results of these studies indicate the turbine as an attractive solution to improve the performance of hybrid propulsion systems. A study on performance of a micro gas-steam turbine combined cycle (MCC) unit operating with natural gas (compressed natural gas – CNG – application) was developed by authors and results are presented in the paper. In the transportation field, natural gas represents a very attractive and promising alternative fuel to the gasoline, methanol or diesel due to cleaner combustion qualities and low cost [15].

The opportunity of the study on MCC implementation in the area of hybrid propulsion systems, which implies a low power level, is supported by the impressive performance of high and medium power combined cycles power stations, which currently are the most efficient and least polluting power units operating with fossil fuels. Compared to studies conducted in [13] (gas turbine without heat exchanger and steam cycle with one pressure level) and [14] (gas turbine with heat exchanger and steam cycle with two pressure levels), the analysed configuration is based on a gas turbine with heat exchanger and a steam cycle with one pressure level.

2. Description of the hybrid propulsion system

Schematic of the analysed MCC hybrid system is shown in figure 1 and has a series-parallel topology, which was chosen due to a good flexibility and high efficiency. This configuration not only ensures flexibility [16], but allows the turbines to operate mainly in optimum conditions, at rated rotation speeds. Accordingly, efficiency is maintained high in each operating mode. Also, when compared to other powertrain architectures, the series-parallel topology makes possible regenerative braking [17].

![Figure 1. Layout of hybrid system based on micro gas-steam turbine combined cycle unit.](image-url)
The flue gas exiting the gas turbine passes through heat exchanger HE preheating the air entering the combustion chamber of the gas turbine engine (GTE). After HE, the flue gas passes through heat recovery steam generator (HRSG) – the link between GTE and the steam turbine engine (STE) – and then are released into the atmosphere. Thus, the waste heat from GTE is partially recovered in STE, which produces additional power; hence, MCC converts fuel into mechanical energy more efficiently than GTE in single operation. But the use of STE implies the presence of the condensing system. The typical condensing system, with cooling tower, induces water losses, which can not be accepted in the case of a propulsion system of an on-road vehicle. That is why the condensing system type included into the analyzed scheme operates in closed cycle: condensate is subcooled by air in a heat exchanger CHE, then a fraction of the subcooled condensate flow is sprayed into the steam turbine exhaust flow and thus steam condensation occurs.

3. Method

The performance of MCC hybrid system presented in figure 1 was analysed by computing the output power, efficiency and specific fuel consumption according to [18], as described below.

Output power of MCC represents the sum of the output powers produced by GTE and STE, in kW,

$$P_{MCC} = P_{GTE} + P_{STE} = \eta_m \cdot w_{GTE} \cdot m_s \cdot \left[ (AER \cdot AFR)^{-1} + 1 \right] \cdot (1 - \theta_{a}) + (m_s \cdot \Delta h_{ST} - m_{ES} \cdot \Delta h_{ES})$$  \hspace{1cm} (1)

where: \( \eta_m \) is the mechanical efficiency of turbines; \( w_{GTE} \) represents the specific work output of GTE, in kJ/kg; \( m_s \) is the inlet mass flow rate of the compressor, in kg/s; \( AER \) is air excess ratio; \( AFR \) is air-fuel ratio, in kg air/kg fuel; \( \theta_{a} \) represents the fraction of air mass flow rate used for cooling of turbine nozzles; \( m_s \) and \( m_E \) are the steam turbine inlet mass flow rate (point 1 in figure 1) and extraction steam mass flow rate (point 2), respectively, in kg/s (they result from the thermal balances of HRSG and deaerator); \( \Delta h_{ST} \) represents the total change of specific enthalpy in the steam turbine (from point 1 to point 3), in kJ/kg; \( \Delta h_{ES} \) is the change of specific enthalpy in the steam turbine from the extraction section (point 2) to the turbine exhaust (point 3), in kJ/kg.

Efficiciencies of the two turbine engines of the MCC unit, i.e. GTE and STE, were calculated with

$$\eta_{GTE} = 3.6 \cdot P_{GTE} \cdot (FC_{MCC} \cdot LHV)^{-1} \cdot 10^5 \hspace{1cm} (2)$$

$$\eta_{STE} = P_{STE} \cdot (m_{s} \cdot \Delta h_{HRSG})^{-1} \cdot 10^2 \hspace{1cm} (3)$$

while overall efficiency of the MCC was expressed as

$$\eta_{MCC} = 3600 \cdot P_{MCC} \cdot (FC_{MCC} \cdot LHV)^{-1} \cdot 10^5 \hspace{1cm} (4)$$

The terms \( FC_{MCC}, \ LHV, \ m_s, \) and \( \Delta h_{HRSG} \) in formulas (2), (3) and (4) denote fuel (natural gas) consumption of MCC unit, in Nm³/h, lower heating value of fuel, in kJ/Nm³, flue gas mass flow rate, in kg/s, and the change of the flue gas specific enthalpy in HRSG, in kJ/kg.

Fuel consumption, in Nm³/h, was given by

$$FC_{MCC} = 3600 \cdot m_{s} \cdot (\rho_f \cdot AER \cdot AFR)^{-1} \cdot (1 - \theta_{a}) \hspace{1cm} (5)$$

where \( \rho_f \) is fuel density, in kg/Nm³.

Specific fuel consumption, in Nm³/kWh, was calculated with the classic formula

$$SFC_{MCC} = FC_{MCC} \cdot P_{MCC}^{-1} \hspace{1cm} (6)$$

In order to assess the environmental impact of MCC hybrid system unit, CO₂ emission rate, expressed in gCO₂/kWh, was calculated with formula
\[ E_{CO2} = 1000 \cdot SFC_{MCC} \cdot g_C \cdot \rho_f \cdot M_{CO2} \cdot M_C^{-1} \]  

where \( g_C \) is the carbon fraction in the fuel, in kg carbon/kg fuel, while \( M_{CO2} \) and \( M_C \) are the molar masses of carbon dioxide and carbon, respectively.

The study was conducted by assuming that inlet mass flow rate of the compressor \( (m_{ia}) \), gas turbine inlet temperature and temperature of flue gas exhausted from HRSG are 0.45 kg/s, 1400 K and 393 K, respectively. A minimum temperature difference of 20 K was accepted between the temperature of flue gas exhausted from HRSG and temperature of superheated steam. Pressure loss in the combustion chamber of GTE and combustion efficiency were assigned 3% and 98%, respectively. Mechanical efficiencies of gas turbine and steam turbine were assumed 99% while isentropic efficiencies of these two turbines as well as isentropic efficiency of compressor were assigned 86%. The fraction of air mass flow rate used for cooling of turbine nozzles \( (\theta_{ca}) \) was assumed 3%. It was considered a condensing pressure of 0.4 bar, which induces a saturation (condensing) temperature of 75.9°C.

The following values were determined: \( AFR = 16.57 \text{ kg air/kg fuel}, \) \( LHV = 34062.9 \text{ kJ/Nm}^3, \) \( \rho_f = 0.714 \text{ kg/Nm}^3 \) and \( g_C = 0.726 \text{ kg C/kg fuel}. \)

The terms \( T_{ai}, T_{ao}, \) and \( T_{gi} \) are expressed in K.

The study was undertaken to evaluate MCC unit performance and effectiveness of GTE heat exchanger, defined as (see figure 1):

\[ \sigma_{HE} = \frac{T_{ao} - T_{ai}}{T_{gi} - T_{ai}}, \]

as a function of GTE compressor pressure ratio, \( \pi_c \), and characteristic temperature difference of GTE heat exchanger, \( \Delta T_{HE} \), which is given by

\[ \Delta T_{HE} = T_{gi} - T_{ao}. \]

4. Results and interpretation

The terms \( T_{ai}, T_{ao}, \) and \( T_{gi} \) in equations (8) and (9) denote air inlet temperature, air outlet temperature and flue gas temperature at GTE heat exchanger inlet, expressed in K.

The results of the analysis are graphically represented in figure 2 and figure 3. It can be seen that maximum value of \( \pi_c \) is 14 when \( \Delta T_{HE} = 60 \text{ K} \) and decreases gradually (down to 9) when \( \Delta T_{HE} \) increases (up to 240 K). This is because \( T_{ao} \) increases with \( \pi_c \), while \( T_{gi} \) decreases as long as gas turbine inlet temperature is constant, so less and less heat is transferred from flue gas to air in GTE heat exchanger until it becomes zero, which means that the use of GTE heat exchanger becomes meaningless at a certain value of \( \pi_c \) (the maximum possible one).

Figure 2a clearly shows that both \( P_{GTE} \) and \( P_{STE} \) increase with \( \pi_c \), but decrease with \( \Delta T_{HE} \). As consequence, \( P_{MCC} \) (the sum of \( P_{GTE} \) and \( P_{STE} \)) exhibits the same trends. By analysing figure 2b and figure 3b, it can be observed that the rate of heat exchanged in HE, emphasized by \( \sigma_{HE} \), influences decisively the value of \( \eta_{GTE} \). Thus, lower values of \( \pi_c \) and/or \( \Delta T_{HE} \) lead to the increase of \( \sigma_{HE} \), which induces the increase of \( \eta_{GTE} \). But lower values of \( \pi_c \) and/or \( \Delta T_{HE} \) also induce lower temperature of the flue gas exhausted from GTE \( (t_{go}) \), so less heat is introduced in the steam cycle where this heat is converted less efficiently into power (see variations of \( P_{STE} \) and \( \eta_{STE} \) in figure 2a and figure 2b). Consequently, STE performance has the lowest influence on the performance of MCC unit when \( \pi_c \) and \( \Delta T_{HE} \) are the lowest. In an opposite approach, the increase of \( \pi_c \) and/or \( \Delta T_{HE} \) leads to STE performance improvement. Thus, both \( P_{STE} \) and \( \eta_{STE} \) increase and compensate more effectively the GTE performance loss when \( \pi_c \) and \( \Delta T_{HE} \) increase. Hence, \( \eta_{MCC} \) varies in a quite narrow range compared to \( \eta_{GTE} \) and \( \eta_{STE} \).

It must be noted that, in spite of the effective compensation, the performance of MCC unit is higher when \( \pi_c \) and \( \Delta T_{HE} \) exhibit low values. This emphasizes that the rate of heat conversion into power
should be maximized in GTE and not in STE. Besides, it is highlighted the role of STE as waste heat recovery unit.

![Figure 2](image1.png)

**Figure 2.** Output powers (a) and efficiencies (b) versus GTE compressor pressure ratio for several temperature differences of GTE heat exchanger.

![Figure 3](image2.png)

**Figure 3.** Specific fuel consumption / CO₂ emission rate (a) and effectiveness of GTE heat exchanger (b) versus GTE compressor pressure ratio for several temperature differences of GTE heat exchanger.
Taking into account the discussion above, yields that highest performance level of MCC unit is achieved when \( \pi_c \) and \( \Delta T_{HE} \) have minimum values, namely 5 and 60 K, respectively. In this case, \( \sigma_{HE}, \eta_{GTE} \) and \( \eta_{MCC} \) attain their maximum values, of 0.91, 46.7% and 49.6%, respectively, \( \eta_{GTE}, SFC \) and \( E_{CO2} \) the minimum values, i.e. 9.8%, 0.241 Nm\(^3\)/kWh and 457.1 g\( \text{CO}_2 \)/kWh, while \( P_{MCC} = 408.5 \) kW. These values indicate the significantly higher performance potential of the analysed MCC unit compared to the most advanced diesel ICE (currently the most efficient typical solution for hybrid propulsion), which do not exceed 42% efficiency [19] and have \( \text{CO}_2 \) emission rates higher than 617 g\( \text{CO}_2 \)/kWh [20]. Compared to MCC based on GTE with heat exchanger and steam cycle with two pressure levels, studied in [13], with \( \eta_{MCC} = 49.6\% \) and \( SFC = 0.242 \) Nm\(^3\)/kWh, MCC unit analysed in this paper offers similar performance but in a simpler version, with a simpler construction of both HRSG and steam turbine, which is possible due to the single pressure level in the steam cycle. Accordingly, the analysed hybrid propulsion system based on MCC unit represents an interesting alternative solution for conventional hybrid propulsion systems with ICE.

5. Conclusions

In order to maximize the performance of MCC unit, the performance of GTE should be maximized since it converts heat into power more efficiently than STE, which plays the role of a waste heat recovery system.

The performance of the analysed MCC unit operating with CNG – characterized by maximum efficiency, minimum SFC and minimum \( \text{CO}_2 \) emission rate values of 49.5\%, 0.241 Nm\(^3\)/kWh and 457.1 g\( \text{CO}_2 \)/kWh, respectively – is considerably higher compared to the most advanced diesel ICE that are currently used as typical instantaneous power generation source for hybrid vehicles. Besides, it offers the same performance with MCC based on STE with two pressure levels, which has a more complex construction. Due to these aspects, it can be assumed that hybrid propulsion system consisting of GTE with heat exchanger and STE with one pressure level represents a noticeable alternative to the typical hybrid system, based on ICE.

The main concern in further studies on MCC units for hybrid on-road propulsion should be related to the development of micro steam turbines with output powers less than 50 kW and to micro gas turbines operating with high temperature and pressure of flue gas.

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