Micro gas and steam turbines power generation system for hybrid electric vehicles

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Abstract. Hybrid electric vehicles (HEV) are currently considered a viable solution for fossil fuel saving and pollutant emissions reduction in transportation sector. The typical HEV configuration contains a reciprocating internal combustion engine – gasoline or diesel. Aiming to increase performance and reduce pollution, a study on performance, size and mass of a HEV configuration with micro gas and steam turbine was developed. The proposed system generates 100 kW output power and operates with compressed natural gas (CNG hybrid technology), which is a fuel more environmentally friendly than gasoline or diesel. The study revealed that analysed system performs better than most advanced equivalent ICE engines while its size and mass fit into the bodywork of a car. A solution for arrangement of the system components in the case of a car is also presented.

1. Introduction

The concerns regarding fossil fuels depletion and environmental impact of the pollutant / greenhouse emissions (estimations from 2014 indicated that global emissions of CO₂ caused by transportation will be doubled by 2050 [1]) have led to a continuous intensification of studies for alternative technologies in road transport. The most promising of them is based on electric propulsion.

Depending on the specific type of propulsion technology, the electric vehicles are usually classified into three main categories: Electric Vehicles (EV), Plug-in Hybrid Electric Vehicles (PHEV) and Hybrid Electric Vehicles (HEV); recent studies developed in USA [2] indicate the latter as most energy efficient. Anyway, all electric propulsion technologies are based on batteries and/or supercapacitors as energy storage devices. That is why several studies are currently focused on these devices, which decide – partially or entirely – the driving range of the vehicle and have a significant contribution in its price. A suitable solution for EV are Li-ion batteries. Currently, their use is still limited by poor performance at low temperatures, [3]. Another problem related to energy storage devices is handling the variable energy consumption and frequent changes that occur in the battery discharging process. A proper solution [4] is to couple batteries with supercapacitors, which can provide additional energy when batteries are not able to do it.

EV are based only on batteries and/or supercapacitors. They are not very popular yet because of the high cost, limited facilities for batteries charging and limited driving range compared with conventional vehicles [5]. PHEV and HEV also include batteries/supercapacitors, but incorporate a supplemental source for instantaneous generation of power, which compensate – partially or entirely – technical drawbacks of batteries. Usually, this source is a reciprocating internal combustion engine (ICE) – gasoline or diesel.
Hybrid vehicles achieve significant fuel savings. Examples presented in literature [1] indicate fuel savings relative to conventional vehicles of 25.5 - 53.6 % in China and 13.2 - 32.6 % in USA; the different results for the two countries occur from different driving conditions. According to [6], amounts of money spent annually in Japan by owners of hybrids and gasoline vehicles are quite similar, but hybrid vehicles imply much lower travel costs per-kilometer even if depreciation cost and taxes are accounted. In spite of fuel savings, adoption of HEV is not always the optimal financial option without subsidies [7]. That is why subsidies could be a real solution for many countries in trying to cope with environmental threat [8].

With respect to diesel hybrids, the real-world tests [9] indicate a significant discrepancy between on-road and certified emissions. These tests revealed NOX and CO2 emissions exceeding admitted limits in Euro standards – with 150 - 550 % for NOX and 52 - 178 % for CO2.

Aiming to lessen emissions and fuel consumption, a hybrid vehicle with additional solar modules was analyzed [10] from the point of view of cost and CO2 emissions associated to manufacturing process. An experimental study [11] indicates that 13.4 km could be added to the driving range by including a 200 W photovoltaic module in the hybrid power source of a vehicle with a weight of 1880 kg and equipped with a 19.2 kWh Li-ion battery.

Beside ICEs, another solution for instantaneous power generation source, promising higher performance and also based on fossil fuel, is the fuel cell [12], [13].

Micro gas turbine (MGT), which is lighter and produces less emissions than an ICE, was also investigated as range extender for EV. MGT could ensure an EV driving range similar to ICE or as range-extender for EV [14], [15]. The present study also refers to a micro turbine solution to be integrated into a HEV. But, compared to the previously analyzed solutions, the present one is based on a combined cycle scheme, including both micro gas and steam turbines (MGST). This technology is currently available only at high and medium powers where stations based on this concept – combined cycle power plants - are the most efficient and least pollutant fossil fuel power stations. Performances size and mass of the proposed MGST power system are analyzed in the paper.

2. Description of the micro turbine hybrid system

The analysed MGST hybrid system is presented in figure 1. Due to the high flexibility and efficiency of operating modes [16], a series-parallel configuration of the powertrain was considered. Thus, turbines speeds are not dependent upon the vehicle/wheels speed. Consequently, they can operate mostly in optimum operating conditions. This is very important for turbine engines since performances are more sensitive to the rotation speed. Besides, series-parallel architecture of the drivetrain makes possible regenerative braking, opportunity charging, EV-only mode as well as MGST-only mode.

The analysis of MGST was performed considering compressed natural gas as fuel, which is more economical than gasoline or diesel (profits up to 25 %/15 % higher than gasoline/diesel) and more environmental friendly (up to 95 %/30 %/87 % less CO/CO2/NOx emissions) [17]. Thus, the proposed system represents a CNG hybrid technology. Compared to other configurations studied, MGT flue gas are passing the heat recovery steam generator (HRSG) before being released into the atmosphere and a part of MGT waste heat is recovered in the steam cycle. Steam produced by HRSG drives ST, which generates additional power. Consequently, efficiency of fuel conversion into useful mechanical energy increases.

In order to avoid the water loss associated with a conventional condensing system (with cooling tower) it was adopted a condensing solution with forced convection heat exchanger and spraying of a subcooled condensate fraction into the ST exhausted steam.

3. Method of analysis

Performances of MGST system were estimated as in [18] expressing efficiency ($\eta_{MGST}$), output power ($P_{MGST}$), fuel consumption ($FC_{MGST}$) and specific fuel consumption ($SFC_{MGST}$). Efficiency of MGST, in %, was expressed as
Figure 1. Schematic of the gas and steam micro turbine hybrid system.

\[
\eta_{MGST} = 3.6 \cdot 10^4 \cdot P_{MGST} \cdot \left( LHV_{NG} \cdot FC_{MGST} \right)^{-1},
\]

where \( LHV_{NG} \) is the lower heating value of the natural gas, in kJ/Nm\(^3\). Output power of MGST, from formula (1), is the sum of the output powers generated by gas power turbine \( PT \) and steam turbine \( ST \) (see figure 1), in kW

\[
P_{MGST} = P_{PT} + P_{ST}.
\]

Efficiencies of the two component engines of MGST – micro gas turbine engine (MGT) and micro steam turbine engine (MST) – were given by

\[
\eta_{G} = 3.6 \cdot 10^4 \cdot P_{PT} \cdot \left( LHV_{NG} \cdot FC_{MGST} \right)^{-1},
\]

\[
\eta_{ST} = 100 \cdot P_{ST} \cdot \left( \dot{m}_k \cdot \Delta h_{HRSG} \right)^{-1},
\]

where \( \dot{m}_k \) is the mass flow rate of flue gas, in kg/s, while \( \Delta h_{HRSG} \) is specific enthalpy change of the flue gas in HRSG (from the entrance to the exit), in kJ/kg.

The output powers of the MGT and MST, in kW, were expressed as

\[
P_{PT} = 0.01 \cdot \dot{m}_{air} \cdot w_{PT} \cdot \eta_{mGT} \cdot \left[ 1 + (AFR \cdot AER)^{-1} \right] \cdot \left( 1 - 0.01 \cdot \theta \right),
\]

\[
P_{ST} = 0.01 \cdot \eta_{mST} \cdot \left( \dot{m}_s \cdot \Delta h_{ST} - \dot{m}_E \cdot \Delta h_{ES} \right),
\]

where \( \eta_{mGT} \) and \( \eta_{mST} \) are mechanical efficiency of gas and steam turbines, in %; \( \dot{m}_{air} \) is air mass flow rate at compressor inlet, in kg/s; \( w_{PT} \) is specific work of PT, in kJ/kg; \( AFR \) is air-fuel ratio (stoichiometric), in kg of air per kg of fuel; \( AER \) is air excess ratio; \( \theta \) is fraction of turbine cooling air mass flow rate, in %; \( \dot{m}_s \) is steam mass flow rate at ST inlet (in point 1 – see figure 1), in kg/s; \( \dot{m}_E \) is extraction steam mass flow rate (in point 2), in kg/s; \( \Delta h_{ST} \) is the total specific enthalpy change in ST (from point 1 to point 3), in kJ/kg; \( \Delta h_{ES} \) is specific enthalpy change in ST from the steam extraction point to the outlet (from point 2 to point 3), in kJ/kg.
Mass flow rates $\dot{m}_E$ and $\dot{m}_S$ were obtained from thermal balances of deaerator and HRSG. Fuel consumption of GSMT, in Nm$^3$/h was calculated as

$$ FC_{MGST} = 36 \cdot \dot{m}_{air} \cdot (100 - \theta_{air}) \cdot \left(AFR \cdot AER \cdot \rho_{NG}\right)^{-3}, \quad (7) $$

where $\rho_{NG}$ is the absolute density of natural gas, in kg/Nm$^3$.

Once known $P_{MGST}$ and $FC_{MGST}$, specific fuel consumption, in Nm$^3$/kWh was expressed as

$$ SFC_{MGST} = FC_{MGST} \cdot P_{MGST}^{-1}. \quad (8) $$

As a measure of environmental impact of the proposed propulsion system, CO$_2$ emission rate, in gCO$_2$/kWh, was calculated as

$$ E_{CO2} = 10^3 \cdot \rho_{NG} \cdot \theta_c \cdot M_{CO2} \cdot M^{-1} \cdot SFC_{MGST}, \quad (9) $$

where $\theta_c$ is the carbon content of the natural gas, in kg of carbon per kg of fuel; $M_{CO2}$ is the molar mass of carbon dioxide; $M$ is the molar mass of carbon.

Size and mass of MGST are overwhelmingly settled by condensing system heat exchanger (CSHE) and constituent components of HRSG (economizer, vaporizer and superheater). That is why volume and mass of these components were calculated. The first step was to express their heat transfer areas, in m$^2$, with typical formula

$$ A_{HE} = \dot{Q}_{HE} \cdot \left(U \cdot \Delta T_{in}\right)^{-1}, \quad (10) $$

where $\dot{Q}_{HE}$ is the rate of the heat transferred, in W; $U$ is the overall heat transfer coefficient, in W/(m$^2$ K); $\Delta T_{in}$ is the log mean temperature difference, in K.

Rate of heat transferred, in W, was given by

$$ \dot{Q}_{HE} = 10^3 \cdot \dot{m} \cdot \Delta h, \quad (11) $$

where $\dot{m}$ is the cold fluid mass flow, in kg/s, while $\Delta h$ is the change of the cold fluid specific enthalpy in heat exchanger, in kJ/kg.

Overall heat transfer coefficient was given by

$$ U = \psi \cdot \left(h_{c}^{-1} + h_{h}^{-1}\right)^{-1}, \quad (12) $$

where $\psi$ is the effectiveness coefficient of the heat exchanger while $h_{c}$ and $h_{h}$ are convection heat transfer coefficients of hot fluid and cold fluid, respectively, in W/(m$^2$ K).

The two convection heat transfer coefficients were expressed as

$$ h_{h,c} = \lambda_{h,c} \cdot Re_{h,c}^{m} \cdot Pr_{h,c}^{n} \cdot d^{-1} \cdot A \cdot C, \quad (13) $$

where $\lambda_{h,c}$ is hot/cold fluid thermal conductivity, in W/(m K); $Re_{h,c}$ is Reynolds number of hot/cold fluid; $Pr_{h,c}$ is Prandtl number of hot/cold fluid; $d$ is the tube diameter, in m; $A$ is a coefficient depending on the flow type; $C$ is a correction factor depending on the heat exchanger geometry and flow type.

Volumes, in m$^3$, and masses, in kg, of CSHE and HRSG heat exchangers are expressed as functions of calculated areas as follows

$$ V_{CSHE,HRSG} = sv_{CSHE,HRSG} \cdot A_{CSHE,HRSG}, \quad (14) $$

$$ m_{CSHE,HRSG} = ma_{CSHE,HRSG} \cdot A_{CSHE,HRSG}, \quad (15) $$

where $sv_{CSHE,HRSG}$ is surface to volume ratio of CSHE/HRSG heat exchangers, in m$^2$/m$^3$; $ma_{CSHE,HRSG}$ is mass to area ratio of CSHE/HRSG heat exchangers, in kg/m$^2$; $A_{CSHE,HRSG}$ is heat-transfer area of CSHE/HRSG heat exchangers, in m$^2$. 
All heat exchangers are tubular type with air/flue gas flowing over the tubes, while water and steam are flowing within tubes. Configuration of heat exchangers were assumed in accordance with [19]. Internal diameter of tubes is 9.53 mm. Both transverse and longitudinal relative pitches are 1.5. The tubes of the CSHE have 0.5 mm thickness while tubes of HRSG heat exchangers have 1 mm thickness. Based on these characteristics, yields $s_{CSHE} = s_{HRSG} = 222.14 \text{ m}^2/\text{m}^3$ and $m_{HRSG} = 2 \times m_{CSHE} = 7.8 \text{ kg/m}^2$.

4. Results and interpretation

Cars represent the vehicles category with most severe technical challenges, since high performance must be ensured at low power and in conditions of smallest available space. The study was conducted to be relevant for this category of vehicles. An output power of 100 kW was assumed as reference for analysed MGST system.

Composition of CNG used as fuel corresponds to the natural gas from Romanian resources. The physical parameters of this fuel are $LHV_{NG} = 34389.9 \text{ kJ/Nm}^3$, $AFR = 17.76 \text{ kg air/kg fuel}$, $\rho_{NG} = 0.713 \text{ kg/Nm}^3$ and $g_c = 0.732 \text{ kg C/kg fuel}$.

The compression ratio of the MGT compressor was considered 6.5. MGT turbine inlet temperature (TIT) and temperature of HRSG outlet flue gas were assumed 1400 K (current advanced materials make possible TIT values up to 1870 K [20]) and 373 K, respectively. Assuming the output power of 100 kW for the analyzed MGST system, as mentioned above, yields the air mass flow rate of $\dot{m}_{air} = 0.2 \text{ kg/s}$ at MGT compressor inlet. The ambient temperature and pressure loss in MGT combustion chamber were 288 K and 3 %, respectively. Mechanical efficiencies and isentropic efficiencies of gas and steam turbines were considered 99 % and 86 %, respectively.

**Table 1.** Performance indicators of MGST.

| Parameter                              | Value  |
|----------------------------------------|--------|
| Gas turbine engine - MGT               |        |
| $\eta_{GT}$ (%)                        | 25.5   |
| $P_{PT}$ (kW)                          | 54     |
| Steam turbine engine                   |        |
| $\eta_{ST}$ (%)                        | 34.1   |
| $P_{ST}$ (kW)                          | 46     |
| Micro gas and steam turbine system - MGST |        |
| $\eta_{MGST}$ (%)                      | 47.3   |
| $P_{MGST}$ (kW)                        | 100    |
| $FC_{MGST}$ (Nm$^3$/h)                 | 22.6   |
| $SFC_{MGST}$ (Nm$^3$/kWh)              | 0.226  |
| $E_{CO2}$ (gCO$_2$/kWh)               | 432    |

**Table 2.** Size and mass indicators of MGST.

| Parameter                              | Value  |
|----------------------------------------|--------|
| Condensing system heat exchanger - CSHE |        |
| $A_{CSHE}$ (m$^2$)                     | 66.5   |
| $V_{CSHE}$ (m$^3$)                     | 0.299  |
| $m_{CSHE}$ (kg)                        | 259    |
| Heat recovery steam generator - HRSG   |        |
| $A_{HRSG}$ (m$^2$)                     | 16.8   |
| $V_{HRSG}$ (m$^3$)                     | 0.076  |
| $m_{HRSG}$ (kg)                        | 131    |
Figure 2. MGST components setting in the case of a car.

Isentropic efficiency of MGT compressor was also assumed 86 %. The pressure and temperature of superheated steam produced by HRSG were considered 160 bar and 560 °C, respectively. A temperature difference of 20 K was considered at both extremities of CSHE – the hot one (condensate at saturation temperature / air after radiator) and the cold one (subcooled condensate / ambient air).
For these conditions, a condensing temperature of 75.9 °C was obtained, with a correspondent saturation (condensing) pressure of 0.4 bar.

Calculated values for performance indicators of MGST are presented in table 1. The temperature of HRSG inlet flue gas (resulted by expressing the expansion process in the gas power turbine PT) was 977 K, while the steam mass flow rate of HRSG and cooling air mass flow rate provided by the fan (figure 1) were 0.043 kg/s and 1.7 kg/s, respectively.

Efficiency of MGST, indicated in table 1, is 47.3 %, which means about 5 % larger than the most performant ICE – the typical solution for HEV/PHEV – that doesn’t break the barrier of 42 % [21]. Moreover, CO₂ emission rate of MGST (432 gCO₂/kWh) are about 30 % lower than CO₂ emission rates of most advanced ICE (diesel), which are above 617 gCO₂/kWh, as indicated in [22].

Micro steam turbine of MGST should provide 46 kW. Currently, on the market are available micro steam turbines providing even lower powers, down to 15 kW, but they operate with low steam parameters [23]. That is why researches on micro steam turbines operating with high steam parameters should represent a priority for next studies on GSMT hybrid system.

Dimensional and mass indicators of MGST were calculated as presented in section 3 and shown in table 2. It can be observed that CSHE is about four times larger than HRSG heat exchangers altogether (0.299 m³ versus 0.076 m³) and about two times heavier (259 kg versus 131 kg). Nevertheless, CSHE and HRSG could be fitted within a car bodywork. There are also solutions for significant compactness of heat exchangers if required; obviously, the greatest benefits are achieved when it refers to CSHE. A proposed solution is water spraying in cooling air mass flow, as the overall heat transfer coefficient may be increased up to 1.73 times, [24].

Figure 2 shows a proposed solution for MGST components arrangement within the bodywork of a car with dimensions 4.25 m (length) × 1.74 m (width) × 1.53 m (height), corresponding to Dacia Logan car model. The heat exchangers are occupying just partially the inside flue duct of HRSG; this duct could be significantly shortened if more convenient solutions for flue gas connections are found. For clarity, the other components of the hybrid system – battery, inverter, motor and generator – were not represented in this figure to avoid overlap. Except for battery, located under the backseat, the other components are placed in the front side of the car, being framed by HRSG. CSHE was divided into two parts (25 and 26 in figure 2) for more flexibility of its placement.

### 5. Conclusions

The studied propulsion system combines three top technologies of clean power generation and propulsion sectors, namely combined cycle power units, hybrid systems and CNG technology.

The analysed MGST, of 100 kW, matches the usual level of power required for car propulsion. MGST is significantly more efficient than most advanced ICE (47.3 % versus 42 %), which currently are the typical solution for car propulsion, as stand-alone units or in hybrid configuration.

MGST has CO₂ emissions rate about 30 % lower than most advanced ICE diesel engines used in terrestrial propulsion – 432 gCO₂/kWh versus 617 gCO₂/kWh.

Volumes of CSHE and HRSG heat exchangers (0.299 m³ and 0.076 m³) – the component with decisive role in what concerns size and mass of MGST – allows the MGST fitting within the car bodywork. A solution for MGST components arrangement in the case of a car with dimension of Dacia Logan model is presented.

Significant compactness of MGST would be achieved by enhancing heat transfer in CSHE. A very efficient solution is the use of water spraying in the cooling air, which could reduce volume and mass of CSHE up to 1.73 times.

Further studies on MGST hybrid system should be concerned with research on micro steam turbine with high steam parameters.

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Acknowledgments
This work was partly supported by the project POSCCE-A2-O2.2.1-2009-4-ENERED, ID nr. 911, co-financed by the European Social Fund within the Sectoral Operational Program “Increase of Economic Competitiveness”.