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Development of a Test Bench for Biogas-fueled Internal Combustion Engines Working in Cogeneration Mode for Residential Applications

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Abstract. The aim of this paper is the presentation of a test bench developed and installed at the Laboratory of the University of Bologna: the test bench has been developed for internal combustion engines, working as cogeneration units and fueled with biogas. In this perspective, the test bench purpose is to experimentally test and optimize the operation of cogenerative internal combustion engines on varying the boundary conditions, in terms of both biogas composition and electric and thermal load. Other main components are the anaerobic digester, a multi-fuel internal combustion engine, the electric load and a heat exchanger for the heat recovery from the exhaust gases and connected to a water circuit representing the thermal user. The test bench has been equipped with the opportune measurement devices, as well as with a specifically developed data acquisition system. First experimental tests, carried out on varying the methane content within the CH_4-CO_2 blend and the electric load allowed to optimize the test bench in terms of heat recovery section and air supply to the engine.

1. Introduction

Energy self-sufficiency in small remote islands represents an important issue in a sustainability perspective, being these islands often not connected to the natural gas network and partially or not connected to the electric grid. At present, indeed, in such contexts the electricity and domestic hot water needs are commonly fulfilled respectively via diesel generators and electrical boilers [1]. However, these systems are often old and causes a high amount of pollutant emissions, requiring modifications in the years to come in order to achieve the decarbonization goals imposed by European and national legislations [2]. For this reason, new solutions based on renewable energy sources or, in general, on cleaner technologies are being studied. To this respect, a viable solution can be the use of anaerobic digesters (AD) [3], to effectively produce biogas from domestic (and eventually agricultural and/or zootechnical) waste, and the use of the obtained biogas for energy production via combined heat and power units. The biogas production is indeed promoted during the energy transition phase, lying at the intersection of two critical challenges: dealing with the increasing amount of organic waste produced by societies and economies and the need to reduce global greenhouse gases (GHG) emissions [4]. In fact, the production of biogas gives the possibility of continuously using and reusing resources, meeting, at the same time, the rising demand for energy services with better environmental benefits [5]; due to its advantages, biogas production has greatly increased in the last years [6].

However, a complete evaluation on the biogas contribution to the energy sector should include the choice of the technology for the restitution phase (*i.e.*, the production of electricity and heat): indeed, this technological choice could have a relevant impact in the whole energy balance [7]. In this context, biogas can be seen as an energy carrier to generate heat and power through cogeneration systems [8, 9]. In particular, its potential use in heat and power applications has been recently investigated in the state-of-the-art, considering several conversion technologies. Holik et al. [10] examined the utilization of biogas through the Rankine cycle and organic Rankine cycle, optimizing the size of the heat exchangers in the waste heat recovery process. Instead, Fan et al. [11] presented a multi-energy complementary system with biogas cogeneration, showing that biogas cogeneration units can improve the consumption of clean energy, reduce carbon emissions and reduce the system energy cost. In addition, Cao et al. [12] proposed and investigated from thermodynamic and economic viewpoints a novel seasonal combined cycle driven by a biogas-fueled gas turbine. Lantz [13] assessed the economic feasibility of different technologies used to produce heat and power from manure-based biogas. Di Fraia and al. [14] proposed an innovative system for sewage sludge drying, based on the integration of biogas produced by sludge-digestion and solar energy; in the same study, then the biogas is used to fuel a combined heat and power unit (CHP). Finally, Zeng et al. [15] presented a biogas-fueled fuel cell for micro-combined heat and power applications.

In this context, the aim of this paper is the presentation of a test bench developed and installed at the Laboratory of Mechanics of the Alma Mater Studiorum University of Bologna: the test bench has been developed for internal combustion engines (ICEs), working as cogeneration units and fueled with gaseous fuels (pure methane or biogas). The activity, indeed, has been carried out aiming at studying the possibility of using biogas, produced by small anaerobic digesters, to fulfill the needs for electricity and domestic hot water in small islands not connected to the gas network. The originality of this study stands both in the domestic utilization of the biogas, in order to meet the electrical demand of users not connected to the electrical grid and in the size of the considered ICE (2 kW), that results small if compared with other ICEs suitable for biogas applications [16-18].

The test bench purpose is to experimentally test and optimize the operation of cogenerative ICEs by varying the boundary conditions, in terms of both biogas composition and electric load. For this reason and in order to have the highest possible flexibility, in addition to the biogas supply from the digester, the test bench has been provided with two compressed gas cylinders – containing CH_4 and CO_2 respectively – and a specific fuel supply line. In this way, the composition of the CH_4-CO_2 blend representing the biogas can be varied independently from the digester production, allowing to test the ICE operation accordingly. The test bench is able to test an integrated system composed by an anaerobic digester, a multi-fuel internal combustion engine and a heat exchanger for the heat recovery from the ICE exhaust gases, connected to a water circuit representing the thermal user. In addition, the test bench has been equipped with the necessary measurement devices as well as with a specifically developed data acquisition system. In this study, two commercial machines for anaerobic digestion and heat and power production have been tested. In order to characterize the ICE coupled with the AD, an experimental campaign has been conducted. At first, the ICE has been analyzed in its factory set-up, equipped with the original muffler and a heat exchanger placed downstream of the ICE. Then, based on the experimental results of the first campaign, a set-up optimization has been made allowing a maximization of the cogenerative performance of the ICE.

2. Methodology

2.1. Test bench description

In order to study the possibility of using biogas to produce electricity and hot water in small islands not connected to the gas network, a test bench for CHP systems based on the integration of an ICE and of an AD has been developed at the Laboratory of Mechanics of the Alma Mater Studiorum University of Bologna. The layout of the test bench along with the tested systems is shown in Figure 1. The test bench purpose is to experimentally test and optimize the operation of cogenerative ICEs by varying the boundary conditions. In detail, the proposed system, exploiting the organic waste from the user, is able to produce biogas through anaerobic digestion; then, the produced biogas is used as fuel for the ICE, producing electric power and recovering heat from the exhaust gases by means of a heat exchanger connected to a water circuit for the thermal user emulation.

The main analyzed components are:

- the AD, developed by HomeBiogas [19], able to decompose organic waste (inserted into the digester via the inlet sink) and to transform it into renewable biogas; this device shows a gas tank volume equal to 700 l and a maximum daily quantity of processable organic waste up to 6 l/day;
- the ICE (Figure 2), developed by GRETECH [20] and rated for an electrical power output of 1.35 kW when fueled with biogas. This particular device is indeed a multi-fuel internal combustion engine, able to exploit gasoline, natural gas (NG), liquefied petroleum gas (LPG) and biogas as fuel;
- a compressed cylinder for the carbon dioxide, with a capacity of 40 l and with a maximum pressure of 40 bar;
- a compressed cylinder for the methane (purity 3.0 – 99.9 %), with a capacity of 40 l and with a maximum pressure of 200 bar;
- a shell heat exchanger, produced by dpPerformance GmbH [21] and rated for a maximum thermal power of 54 kW.

Figure 1 shows also several pressure reducers installed in the test bench to control the pressure levels in the different sections. In more detail, two first-stage pressure reducers have been installed in the methane and carbon dioxide supply lines, showing for both a maximum input up to 300 bar and an output in the range 0–20 bar. A supplementary second-stage pressure reducer (outlet pressure in the range 0–4 bar) has been installed in the system in order to regulate the pressure level in the feed line of the ICE (recommended input pressure in the range 2–6 bar for the analysed system [20]). In addition, a non-return valve has been placed in the fuel supply line.

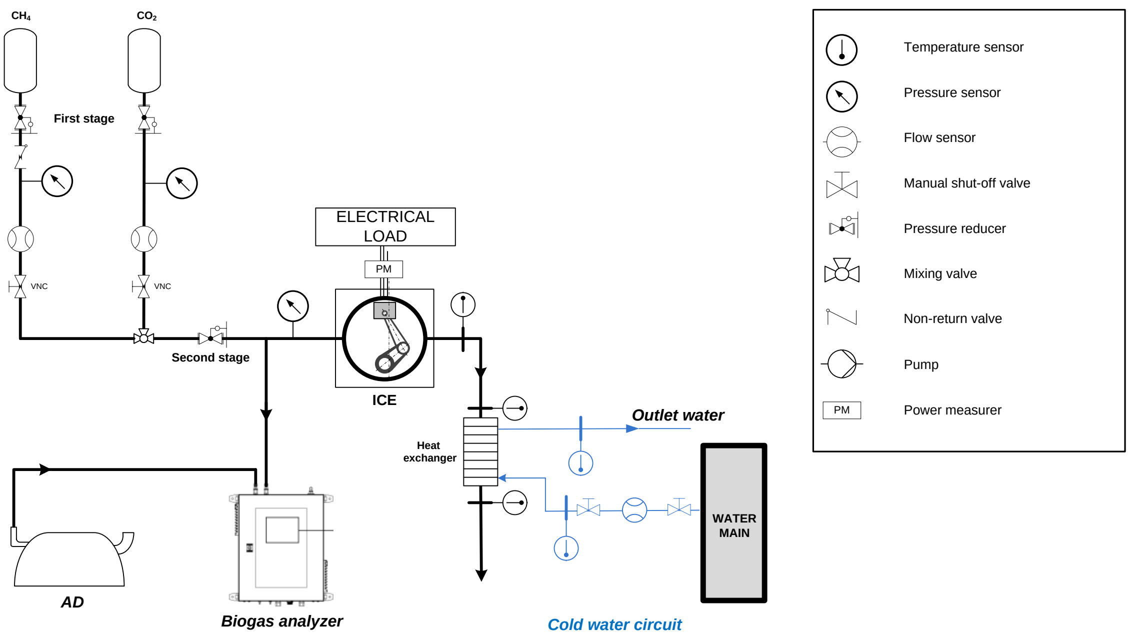


Figure 1. Schematic of the developed test bench supplied by methane and carbon dioxide.

Figure 2. The multi-fuel internal combustion engine developed by GRETECH [20].

The test bench has been equipped with several sensors in order to investigate the system behaviour under different boundary conditions. The main specifics of the measurement devices are listed in Table 1. In detail, in order to evaluate the performance of the system, temperature and pressure sensors have been placed at the inlet and outlet of specific components of the system (see Figure 1). Regarding the gas-side, T-type thermocouples for the temperature measurement and absolute ceramic pressure transducers for the pressure measurement have been installed. The thermocouples and the pressure transducers have been calibrated at the laboratory in their operating ranges. A thermal flow meter has been used to acquire the mass flow rate of the methane and of the carbon dioxide at the outlet of the tanks. On the water side, K-type thermocouples have been used to measure cold-water temperature at the inlet and outlet of the heat exchanger. Finally, a magnetic flow meter acquires the flow rate of the water at the inlet of the heat exchanger.

Furthermore, in order to evaluate the gas composition at the inlet of the ICE, a compact analyser has been installed: it is based on an infrared meter to detect methane and carbon dioxide (calibration range 0–100 %). In addition to the composition of the gas, the outputs of the device are: the CH_4 fraction, the CO_2 fraction and the ambient temperature.

The acquired signals are transmitted to a workstation by a National Instrument FPGA device (CompactDAQ). A dedicated real-time data acquisition software has been developed in the LabVIEW environment to control and process the acquired measurements. The CompactDAQ has an 8-slot chassis, in which the following input modules are inserted:

- two NI 9211 modules, for thermocouples' signals;
- a NI 9203 module, for analog electric current signals (0 - 20 mA);
- a NI 9201 module, for analog voltage signals (0 - 10 V).

Table 1. Acquisition system specifications.

Physical quantity	Sensor	Position	Accuracy	Calibration range	Output signal
Gas flow rate	Thermal flow meter	CH_4 and CO_2 tanks outlet	± 1.0 % FS	0 – 1000 Nl/min	4 – 20 mA
Gas composition	Infrared meter	Second-stage pressure reducer outlet		0 – 100 % CH_4 0 – 100 % CO_2	4 – 20 mA
Water flow rate	Magnetic flow meter	Water-side heat exchanger inlet	± 0.5 % RV	0 – 9.8 l/s	4 – 20 mA
Feed pressure	Pressure transducer	ICE inlet	≤ 0.2 % FS	0 – 100 mbar	4 – 20 mA
Mixing pressure	Pressure transducer	First-stage pressure reducers outlet		0 – 15 bar	0 – 10 V
Water temperature	K-type thermocouple	Water-side heat exchanger inlet/outlet	± 0.5 °C	0 – 90 °C	TC
Exhaust gas temperature	T-type thermocouple	ICE outlet, exhaust gas-side heat exchanger inlet/outlet	± 0.5 °C	0 – 90 °C	TC

2.2. Experimental campaign and test bench optimization

In order to characterize the multi-fuel ICE (coupled with the AD) installed at the Laboratory of Mechanics of the Alma Mater Studiorum University of Bologna, a first experimental campaign has been conducted. In particular, in the carried out tests the ICE has been operated in cogeneration mode, with

the heat exchanger placed downstream of the muffler. To ensure greater flexibility and test the ICE independently from the biogas production, but – at the same time – being able to reproduce the AD biogas composition, the tests have been carried out using methane and carbon dioxide cylinders. In particular, in the first set of tests, the ICE has been evaluated with different fuel compositions of CH_4-CO_2 blend: starting from a supply of pure CH_4 (condition usually preferred in the ignition and warm-up phases), the CO_2 valve has been gradually opened, obtaining step-by-step higher percentages of CO_2, up to a mass fraction close to 45 %, corresponding to the experimental value measured in the produced biogas (detected by means of the biogas analyzer described in the above paragraph).
The generator voltage has been kept constant by the mechanical frequency regulation system of the ICE (Watt speedometer) between 220 V and 230 V at a frequency of 50 Hz. The flow rate of the cold water has been set equal to 5 l/min; the water inlet temperature has been kept constant at about 14 °C. As mentioned above, in this first set of tests, the ICE has been analyzed in its factory set-up (see Figure 2), equipped with the original muffler and with a heat exchanger downstream of the ICE connected with a flexible aluminum hose.

Based on the obtained results, since the factory set-up has shown weaknesses for the specific heat and power application, two improvements have been made:
1) modification of the air-fuel ratio at the inlet of the ICE;
2) modification of the exhaust gas line.

In general, the modification of the air-fuel ratio can be operated in two different ways: *i*) regulation of the carburetor (within a given range); *ii*) reduction of the air cross section by introducing a restriction in the duct (with the ICE turned off). In this preliminary study, in the optimized configuration a restriction has been applied. Another inefficiency noticed in the original configuration of the ICE when operated for cogenerative applications is the great heat loss in the exhaust duct. Since the considered ICE is air-cooled, usually it is designed to cool down from the cylinder block walls and then the air-cooled ICE is not completely suitable for heat recovery applications. In the factory set-up, the heat can be recovered only from the exhaust gases, while the heat from the cylinder block is dispersed into the environment. In the optimized configuration, the muffler has been removed and the exhaust pipe has been directly connected to the heat exchanger inlet. The heat exchanger has been insulated with a 10 mm thick rubber hose, suitable to withstand up to 120 °C. In this case, the heat exchanger insulation with the rubber hose was possible, even if it is crossed by hotter gases compared to the original configuration, since the cooling medium is a water stream.

In this second set of tests with the optimized configuration (optimized air stream, muffler removal and heat exchanger insulation), the whole system has been analyzed considering a variable electric load (250 W, 550 W, 1000 W and maximum load) and a variable fuel composition (CH_4 - CO_2 ratio).

2.3. *Performance parameters*
In order to evaluate the performance of the presented system, several parameters have been considered. Due to the heat and power application, at first the system has been assessed from the electrical and thermal viewpoints, by means of the electrical efficiency (η_{el}) and of the thermal efficiency (η_{th}). The considered efficiencies are defined as:

$$\eta_{el} = \frac{P_{el}}{\dot{m}_f \cdot LHV} \tag{1}$$

$$\eta_{th} = \frac{\dot{m}_{H2O} \cdot c_{H2O} \cdot \left(T_{out,H2O} - T_{in,H2O}\right)}{\dot{m}_f \cdot LHV} \tag{2}$$

where P_{el} [kW] is the electrical power produced by the ICE, $\dot{m}_f$ [kg/s] is the mass flow rate of the fuel, LHV [kJ/kg] is the lower heating value of the fuel, $\dot{m}_{H2O}$ [kg/s] is the mass flow rate of the water,

c_{H2O} [kJ/kg·K] is the specific heat capacity of the water and $T_{in,H2O}$ [K] and $T_{out,H2O}$ [K] are, respectively, the temperature of the water at the inlet and at the outlet of the heat exchanger.
Furthermore, the heat exchanger effectiveness (ε_{he}) has been considered, defined as:

$$\varepsilon_{he} = \frac{T_{out,H2O} - T_{in,H2O}}{T_{in,gas} - T_{in,H2O}} \tag{3}$$

where $T_{in,gas}$ [K] is the temperature of the exhaust gas at the inlet of the heat exchanger.
As a result of the heat and power application of the ICE, the overall system has been evaluated by means of the first law efficiency (η_I), in which the electrical and thermal powers have been simultaneously considered:

$$\eta_I = \frac{P_{el} + \dot{m}_{H2O} \cdot c_{H2O} \cdot (T_{out,H2O} - T_{in,H2O})}{\dot{m}_f \cdot LHV} \tag{4}$$

Finally, the advantages of the CHP system with respect to the separate production of electricity and heat have been assessed by means of the primary energy saving (PES) index, defined as:

$$PES = 1 - \frac{1}{\frac{\eta_{el}}{\eta_{el,s}} + \frac{\eta_{th}}{\eta_{th,s}}} \tag{5}$$

where $\eta_{el,s}$ [-] and $\eta_{th,s}$ [-] are, respectively, the reference values of the electrical and thermal efficiency for the separate production of electricity and heat. Due to the application of the paper, $\eta_{el,s}$ and $\eta_{th,s}$ have been set, respectively, equal to 0.40 and 0.89, according to the EU directive [22].

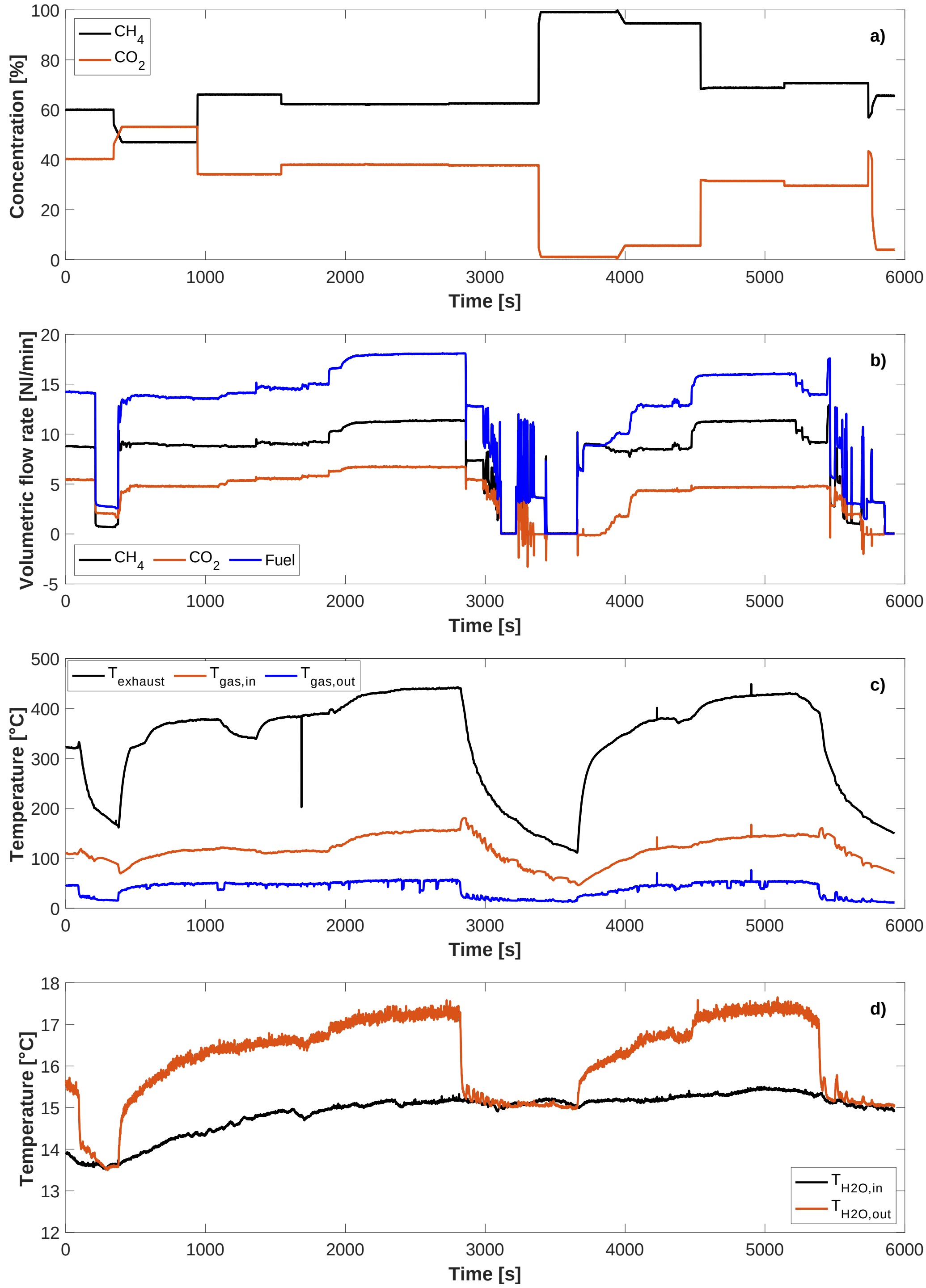
3. Results

In this section, the results of the experimental campaigns are presented. At first, the behaviour of the whole system with the factory set-up is shown. Then, the results of the second set of tests, with the optimized configuration (optimized air stream, muffler removal and heat exchanger insulation) and as a function of the electric load and of the fuel composition, are presented.

3.1. Experimental campaign: factory set-up

The first campaign results include three compositions of the fuel blend (75 % CH_4 – 25 % CO_2, 60 % CH_4 – 40 % CO_2, 55 % CH_4 – 45 % CO_2) and pure methane. In detail, Figure 3a shows the fuel composition variation during the experimental tests, based on the CH_4 and CO_2 concentration, while Figure 3b shows the trend of the volumetric flow rates of CH_4 and CO_2. It should be noted that CH_4 concentrations higher than 75 % (except in the case of pure methane taken as reference) have not been considered since not in line with the composition of the produced biogas. On the contrary, methane concentrations lower than 55 % lead to instability in the ICE operations, highlighted by voltage and frequency decrease at the generator output, up to the extreme case of turning off. Indeed, the ICE operations are very sensitive to fuel composition, since with the increase in the concentration of CO_2 in the fuel, the amount of air required for a stoichiometric combustion decreases. Referring to the temperatures of the exhaust gas and of the water, the results show that with the factory set-up the temperature gap on the gas-side of the heat exchanger is below 100 °C (Figure 3c), while the increase in the water temperature is limited to a maximum of about 3 °C (Figure 3d). From these results, it is possible to calculate the thermal power available to the user; this quantity shows values in the range between 600 W and 900 W, as shown in Figure 3e. The trend of the thermal power is affected by the temperature of the water streams in Figure 3d: positive values of the thermal power are obtained when

$T_{out,H2O} > T_{in,H2O}$, while the thermal power shows negative values when $T_{in,H2O}$ is higher with respect to $T_{out,H2O}$
In Figure 3f the values of η_{th} and ε_{he} are presented. The maximum values for these quantities are, respectively, equal to about 0.28 for η_{th} and about 0.02 for ε_{he}. Regarding the electrical efficiency (η_{el}), it shows a maximum value equal to about 0.24; this result affects the cogeneration efficiency (η_{cog}), that is in the range 0.30-0.40. Finally, the PES shows negative values for most of the analysed points.



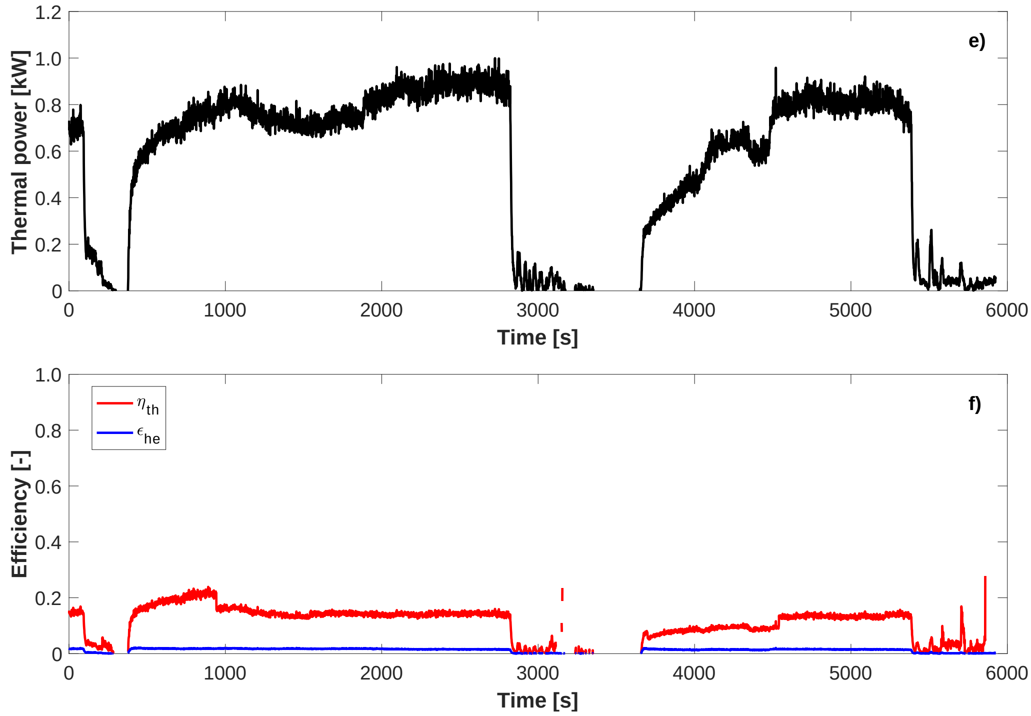


Figure 3. Experimental campaign results for the ICE with the factory set-up: a) CH_4 and CO_2 concentration in the fuel; b) volumetric flow rate comparison; c) temperatures in the heat exchanger: gas side; d) temperatures in the heat exchanger: water side; e) recovered thermal power; f) thermal efficiency and heat exchanger effectiveness.

3.2. Experimental campaign: optimized set-up

In this section, the results for the optimized set-up are presented. In particular, in Figure 4 the efficiency parameters (electrical efficiency – Figure 4a; thermal efficiency – Figure 4b; first law efficiency – Figure 4c; heat exchanger effectiveness – Figure 4d) are shown as a function of the electric load and of the methane content in the fuel blend.

Considering the maximum electrical load, the electrical efficiency is equal to about 20 % for concentrations of CH_4 between 55 % and 75 %, while it is close to 32 % in the case of pure methane. The thermal efficiency shows values higher than 50 % for all the considered concentrations of CH_4, with a peak close to 80 % increasing with the concentration of CH_4; the first law efficiency varies between 60 % and 90 %. Finally, the heat exchanger effectiveness shows values close to 100 %, but heat losses in the exhaust gas side are not considered in equation (4).

Considering, instead, the variation of the electrical load, the electrical efficiency generally increases with the increase in the electrical load and it shows higher values in the case of pure methane; the minimum value is in correspondence of an electrical load of 250 W and is equal to about 5 %. The thermal efficiency is equal to about 60 % for the several configurations, with small variations on the basis of the load conditions. Finally, the first law efficiency shows an increasing trend with the increase in the electrical load.

Regarding the PES, the maximum value (0.22) is obtained at maximum load (Figure 5a) with a high concentration of methane. By decreasing the electric load and the methane content, the PES tends to decrease achieving also negative values: the minimum value (- 0.26) is obtained at the minimum load (250 W – see Figure 5d) and with a concentration of methane equal to 55 %.

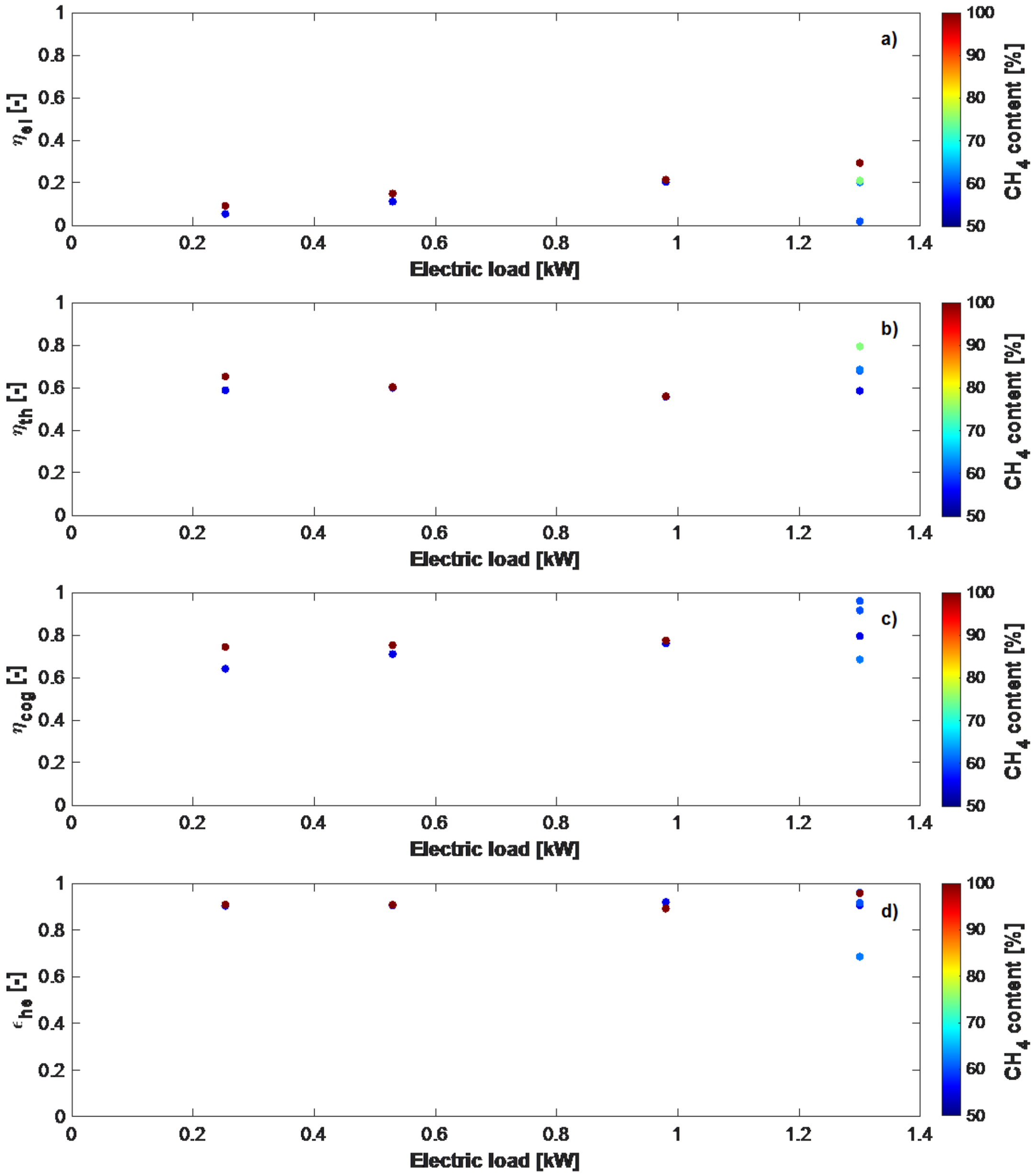


Figure 4. Efficiency parameters as a function of the electrical load and of the methane content in the blend – optimized set-up: a) electrical efficiency (η_{el}); b) thermal efficiency (η_{th}); c) first law efficiency (η_{cog}); d) heat exchanger effectiveness (ε_{he}).

Despite the results, it should be highlighted that the integrated ICE-AD system is not configured to meet the thermal demand of a typical residential user, since it provides a limited amount of thermal power due to the ICE configuration not suitable for an effective heat recovery. Due to the heat and power application of the technology, in case of real application it will be necessary to choose a suitable size.

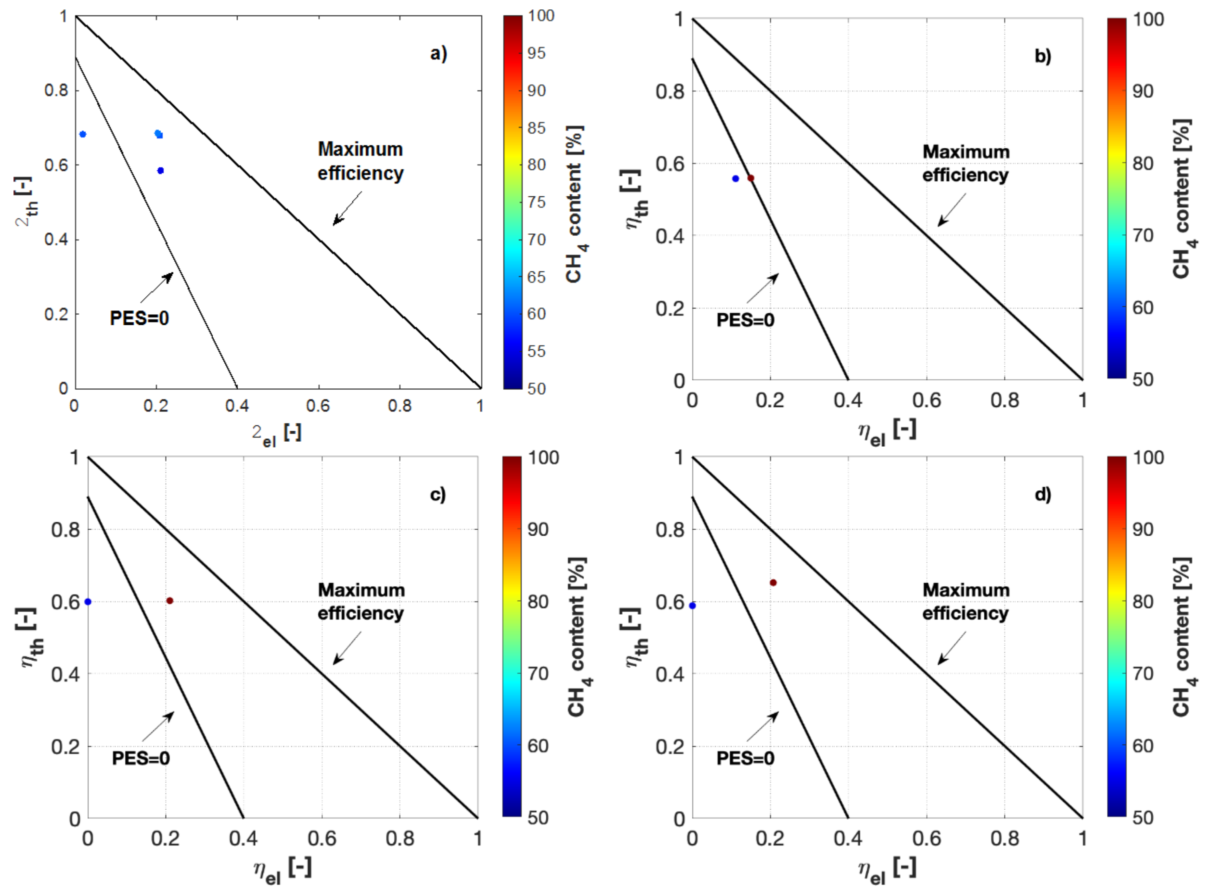


Figure 5. PES analysis results; in the figures, the lines referred to PES = 0 and to the maximum efficiency are highlighted: a) maximum load; b) load = 1000 W; c) load = 550 W; d) load = 250 W.

4. Conclusions

The experimental characterization campaign on the cogenerative system made up of an anaerobic digester and an internal combustion engine, aimed also at validating the optimization strategies implemented on the system, provides the following main findings:

- the biogas produced by the anaerobic digester is in compliance with the quality required for ICE stable operations;
- in order to ensure a proper combustion with the increase in the CO_2 content, a restriction in the air duct is necessary;
- in order to improve the performance of the ICE in cogeneration mode, the configuration of the exhaust gas line has been optimized, through the removal of the muffler; in addition, the heat exchanger has been thermally insulated to further reduce heat losses;
- the results show that the electrical efficiency decreases with the decrease in the electrical load up to a minimum of 5 % at the minimum tested load; the thermal efficiency does not show significant variations on the basis of the load, showing a value of about 60 %;
- the maximum values of the PES (0.22) are obtained at maximum electric load and with a high concentration of methane; by decreasing these two parameters the PES tends to decrease.

Future tests will explore other fuel mixtures, assessing the possibility of using H_2/biogas blends as fuel, as well as other commercial ICE fuelled by different green fuels (biogas, hydrogen-based blends up to 100% of hydrogen content).

5. Nomenclature

AD	Anaerobic Digester
c	Specific heat capacity [kJ/kgK]
CHP	Combined Heat and Power
GHG	Greenhouse Gases
ICE	Internal Combustion Engine
FPGA	Field Programmable Gate Array
FS	Full scale
LHV	Lower Heating Value [kJ/kg]
LPG	Liquefied Petroleum Gas
$\dot{m}$	Mass flow rate [kg/s]
NG	Natural Gas
P	Power [kW]
PES	Primary Energy Saving [-]
PM	Power measurer
RV	Reading value
T	Temperature [K]
TC	Terminal Count

Greek letters

ε	heat exchanger effectiveness [-]
η	efficiency [-]

Subscripts

el	electrical
f	fuel
gas	exhaust gas
he	heat exchanger
I	first law
in	inlet
out	outlet
s	separate
th	thermal

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