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The tests of micro-CHP prototype with SI engine powered by LPG and natural gas

ARTICLE INFO

This paper presents the experimental results of a Combined Heat and Power (CHP) prototype based on a SI V-twin internal combustion engine driving a synchronous generator. The paper presents the criteria that were used to select the combustion engine and the electrical generator for the prototype. The internal combustion engine has been adapted to be fuelled by natural gas or LPG, with the possibility of controlling the load in two ways, i.e. by changing the throttle position (quantitatively) and/or the value of the excess air ratio by changing the fuel dose at a constant throttle position (qualitatively). The applied method of control allows to improve the efficiency of the engine especially in the range of partial loads. The experimental tests were carried out at a constant speed of 1500 rpm. During the tests, the fuel consumption of the internal combustion engine, the composition of the exhaust gas at the outlet of the exhaust system, the electrical parameters of the synchronous generator and the temperature at selected locations of the CHP system instance were measured. According to the obtained results, there was a slight increase in the efficiency of electricity generation with the application of the developed method of control of the combustion engine. The maximum power generation efficiency for Natural Gas (NG) was higher compared to LPG by more than 2 percentage points. The exhaust gas emission level confirm that the prototype cogeneration system meets the Stage II emission standard (in accordance with Directive 2002/08/EC for small SI engines with a power below 19 kW. D2 ISO 8178).

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1. Introduction

Small scale cogeneration units called micro-CHP driven by Internal Combustion Engine (ICE) fueled with gaseous fuels seem to be a promising solution for heat and power generation for householders. The profitability of using such system depends on firstly the investment costs and secondly the operating costs of the mCHP unit. However, an important issue in such case may be the engine lifetime. Another issue is that the electrical efficiency of mCHP units driven by ICE decreases when the electricity demands of the receivers drops. The spark-ignition engine efficiency increases by reducing the pumping loss through the throttle in the partial load range [1]. A simple solution to achieve low pump loss is that using the lean mixture for the partial engine load operation. But, the limitation of using the lean mixture is the flammability limits of the air-fuel mixture of the specific gaseous fuel.

Stirling engines, microturbines, Rankine cycle micro systems, solid-state devices, and fuel cells achieve electrical efficiencies in the range of 30–40% and total CHP efficiency of 80% for a 1 kW device. Achieving these efficiencies, however, is a difficult from both technical and economic point of view to be acceptable for the residential customer [2]. One of the best performing small-scale CHP unit is Vaillant-Honda product based on SI engine with 1.2 kW electrical power with fuel to electricity conversion efficiency of about 26.3% and the total CHP efficiency of 92% [3]. The next examples of mCHP unit that is available on the market is Yanmar mCHP systems. These are based on Miller cycle along with lean air-fuel mixture combustion. The fuel to electricity conversion efficiencies for the 5 kW (CP5WN) and 10 kW (CP10WN) systems are 28% and 31.5%, respectively, with more than 50% thermal efficiencies. Yanmar mCHP systems meet the EPA emissions standard [4, 5]. Dachs 5.5 model is another example of the small scale CHP unit from SENERTEC company. This device offer three output power levels 7.5 kW, 10.6 kW, and 14.8 kW with fuel to electricity conversion efficiencies of 26.5%, 26.5%, and 25.6% respectively which meet German TA-Luft emission standard [6, 7]. The mCHP systems based on ICE are usually available for Liquefied Petroleum Gas (LPG) or NG fuel supply.

In 2018 the natural gas was used in 55.7% of Polish households, but more than half of consumers (51.9%) used it only for cooking, and only 14.0% for space heating. In some areas of the country where have no access to NG, in-cylinders stationary LPG were more common almost 34.0%. The LPG exclusively was used for cooking by more than 99% of consumers [8, 9].

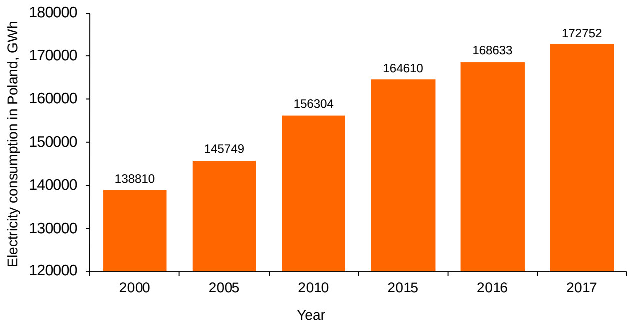


Fig. 1. Electricity consumption in Poland in the years 2000-2017

In the first decade of the 21st century, there was a significant increase in electricity consumption in Poland. In the years between 2000 to 2010, it amounted slightly more than 12%, which is an increase of over 17.4 TWh compared to the value recorded in 2000. Over the next seven years, e.g. in the period of 2010 to 2017, there was a further increase of over 10% [10]. Electricity consumption in Poland between the years from 2010 to 2017 is shown in Fig. 1.

The demand for electricity in Poland will most likely continue to grow in the upcoming years. As mentioned before, a clear upward trend observed in recent decades, can be considered evidence of this statement. In addition, these increase of electricity consumption in the near future will be due to the growing market in sharing of electric and plug-in hybrid vehicles, as well as the growing demand for electricity in households like smart home, air conditioning, etc.

With regard to the data above, the use of local low-power cogeneration systems may be beneficial. The mCHP can be implemented on the basis of an ICE powered by NG or LPG. In the light of the Directive 2004/8/EC, micro-cogeneration refers to the combined production of electricity with a maximum electrical power of less than 50 kW.

This article presents the test results of the prototype equipped in synchronous generator, which was built by Budexpert sp. z o.o. in cooperation with a research team from the Silesian University of Technology as part of a project co-financed from the sources of the Regional Operational Program of the Silesian Voivodeship. A similar study has been conducted previously when using an asynchronous generator and the results were presented in the paper [11].

2. The prototype of mCHP with SI engine

2.1. Selection of SI engine and electric generator

One of the main assumptions for the prototype under construction was to limit the maximum electrical power to approximately 7 kW. The liquid cooled spark ignition engines with a maximum power of less than 10 kW and dedicated to long-term stationary operation are practically unavailable on the market. In the power range below 10 kW, units are available that are used, for example, to drive pumps or emergency power generators. The following criteria were used while selecting the SI engine for the prototype CHP unit:

- availability on the market and the price of the new unit, allowing it to compete in the future with cogeneration set available on the market,
- availability of spare parts,
- maximum power of about 10 kW during continuous operation at a rotational speed of 1500 rpm using standard fuel (i.e. usually gasoline),
- liquid cooling,
- the possibility of modification or replacement of the existing flywheel with a wheel with larger mass and diameter,
- the possibility of easy modification of the inlet system to run on gaseous fuel (NG/LPG),
- start from an electric starter,
- the possibility of modification of the oiling system (adapting the system to the automatic oil dosing system).

Another important aspect was also the factory (or with a slight modification) adaptation of the engine to electronic control, such as a system for determining the position and rotation of the crankshaft, sensors for coolant temperature and inlet air temperature, and a knock sensor and throttle position sensor.

Based on the technical data provided by the manufacturers of drive units, an initial selection of engines meeting the assumed requirements was made. The most important technical data of drive units with an effective power of up to 10 kW are presented in Table 1.

Table 1. Technical data of chosen SI engines

Manufacturer	Kohler			Lombardini		Toyota
Engine type	LH 640	LH 755	LH 775	LGW 523	LGW 627	1KS
Max power [kW]	17.9	20.9	23	15	14,5	21
Power @ 1500 rpm [kW]	6.5	8.5	7.5	5.5	5.4	10.5
Max torque [Nm]	52	61.5	65	37	44.5	75.2
Torque @ 1500 rpm [Nm]	50	56	54	35	39	68
Cylinders	V2	V2	V2	In2	In2	In3
Swept volume [cm^3]	624	747	747	505	611	953
Bore [mm]	77	83	83	72	72	72
Stroke [mm]	67	69	69	62	75	78
Compression ratio	8.5	8.7	8.7	8.7	9	12
Fueling system	Carb	Carb.	Inj.	Carb.	Inj.	Carb.
Weight [kg]	51.7	51.7	51.7	52	52	73.5
Dimensions H/L/W [mm]	674/ 432/ 459	674/ 432/ 459	674/ 432/ 459	484/ 538/ 372	484/ 538/ 372	651/ 488/ 402

The values of the power obtained at 1500 rpm in Table 1 are extrapolated based on the manufacturer's data. It should be noted that the manufacturer's characteristics relate to engine operation on the design fuel, i.e. 95RON gasoline. In order to determine the effective power achieved on gaseous fuels of NG and LPG by the analyzed ICE, calculations were made using the mathematical model characterized in [12]. Taking into account the economic, design, and operational aspects the KOHLER LH775 engine was selected for the prototype.

As part of the analysis of the availability of synchronous generators on the Polish market, the following companies were considered: Leroy-Somer, Mecc Alte, Linz Electric and Marelli Motori. Documentation was analyzed in search of generators with a rotational speed of 1500 rpm, capable to operate in a cogenerator with a electrical power of 7 kW. Technical data of selected generators that meet this criterion are presented in Table 2.

The comparative analysis of generators was carried out by considering minimum rated power (i.e. power for the most difficult winding cooling conditions), maximum rated power (i.e. power for good cooling conditions), maximum efficiency and power in which the generator can achieve the best efficiency. Taking into account the availability of the device and its market price, the Mecc Alte ECP282VS4 generator was selected in order to adapt for parallel operation, for example, factory-installed additional parallel operation system (PD500 + Interface). Additionally, the generator was equipped with a digital voltage regulator DER2 with a communication and programming module via USB.

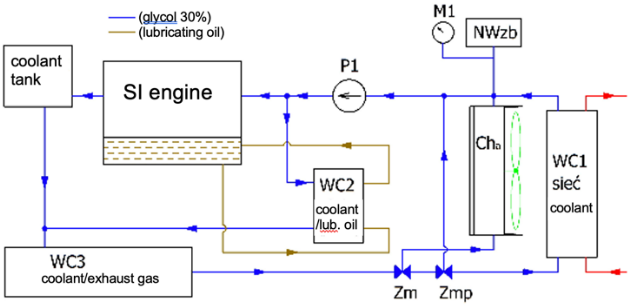
Table 2. Technical data of chosen synchronous generator

Manufacturer	Leroy-Sommer	Mecc Alte	Linz Electric	Marelli Motori
Generator type	LSA40VS1	ECP282VS4	E1X13SC/4	MXB160SA4
Min rated power [kW]	7.2	7.0	7.36	9.2
Max rated power [kW]	8.8	9.0	9.12	11
Max efficiency [%]	88.85	88.5	87.8	81.2
Power @ max efficiency [kW]	8	8.8	7.5	10

2.2. The prototype characteristics

Due to the assumed two methods of controlling the power of engine, it was necessary to develop a dedicated controller to manage the elements of the fuel supply system as well as the ignition system. For this purpose, a project was developed and an prototype ECU was built toward the ability to achieve the goals. The amount of air interring to the engine was controlled by a throttle with a stepper motor. But, the stream of gaseous fuel flow was controlled by an electrically controlled valve. The amount of the excess air ratio was controlled by the signal from the broadband lambda probe installed in the exhaust duct.

The supervisory control system is based on an industrial PLC controller with a network security module. The superior control system ensures a proper operation of the electric part of the cogenerator as well as all elements are related to the heat reception from the ICE. The cogeneration device should have a safe and proper operation in the wide range of every ambient thermal. In the event of operation without heat demand, the heat reception system must ensure its proper discharge to the emergency cooler. Figure 2 shows a diagram of the high-temperature heat reception system from the exhaust gases of the engine, and low-temperature heat from the engine block cooling system and from the oil lubricating the internal of the engine. In order to ensure that system the can operate in a wide range of ambient temperature, a 30% of glycol solution was used as a circulating medium in the heat reception system of the ICE.

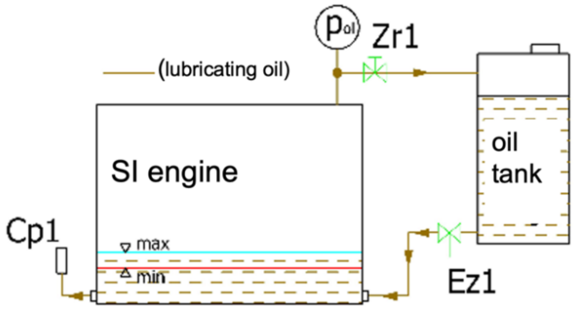


WC1, **WC2, WC3** – the heat exchangers, **P1**$_{\mathbf{z1}}$ – coolant pump, **Ch**$_{\mathbf{a}}$ – emergency radiator, **Ch**$_{\mathbf{a}}$ – emergency radiator, **Zm** – two -state mixing valve, **Zm** – proportional mixing valve.

Fig. 2. Scheme of the heat collection system from the internal combustion engine

In this figure, the blue color represents the glycol flow in the primary circuit of the system, while the red color represents the secondary circuit (heat reception). The brown color represents the flow of lubricating oil of engine. The expansion vessel (NWzb) maintains the required glycol overpressure in the primary circuit, and its value is indicated on the pressure gauge (M1). The pump (P1) pumps glycol to the engine, which during normal operation has been previously cooled in the exchanger (WC1). The glycol stream is partially routed to the heat exchanger (WC2) where it receives heat from the lubricating oil. The remainder of the glycol stream flows through the engine indirectly cooling its internal components by absorbing heat. Then both streams combine and flow into the high-temperature flue gas-glycol exchanger, where the heat is given off as a result of the flue gas enthalpy drop. Then, the glycol flows to the mixing valve (Zm), where enables it redirect to the emergency cooler (Cha) if it is necessary. In the case that when the system works on the heat reception network (Zm), it enables the flow of glycol to the proportional mixing valve (Zmp). This valve distributes the flow between the exchanger (WC1) and the inlet of engine. The valve position depends on the temperature of the glycol at the exit of the engine.

By considering long-term operation of the cogeneration unit, a special engine oil refilling system is provided. Figure 3 shows a diagram of the system of replacement and periodic dosing of engine lubricating oil from an additional reservoir. By default, the bowl of piston holds approximately 3 dm^3 of oil, therefore the constructed reservoir has additional oil of 7 dm^3. The additional volume of oil is refilled from the reservoir. It will allow to the extend the oil change interval also it should increase the durability of the internal components of the engine during operation.



p$_{\mathbf{ol}}$ – lubricating oil pressure transducer, **Z**$_{\mathbf{r1}}$ – throttle valve, **E**$_{\mathbf{z1}}$ – solenoid valve (supply oil circuit), **C**$_{\mathbf{p1}}$ – oil level sensor

Fig. 3. Scheme of the engine lubricating oil refilling system

The prototype engine oil pan is a part of the engine block cast, there are two stub pipes with factory-blinded screws on its opposite side surfaces. The mentioned stub pipes were used to connect the oil dosing system. The measurement of the engine oil level system is mounted to the stub on the drive side of the engine. In turn, an oil reservoir is connected to the stub on the other side of the engine.

The engine lubricating oil is coming from the oil pan and pumped into the lubricating channels and then sprayed onto the internal parts of the engine. There is an oil pressure sensor connected to the channel in the upper part of the engine head. A tee joint is connected to this channel, to which, on one side, a specially selected orifice is connected through the engine lubricating oil (with a very small stream) is directed to the reservoir. The other end of the tee joint is connected to the oil pressure sensor.

During operation, the oil is cycling between the engine and the reservoir. The flow of oil through the orifice, showed in the figure as the throttle valve Zr1, causes loss from the oil pan. After reaching the minimum value which is a safe value for the correct operation of the engine, the oil level sensor system (Cp1) signals the control system, which in turn activates the valve supply circuit (Ez1) and oil is supplied from the reservoir to the engine oil pan. Oil is topped up until the maximum oil level in the oil pan is reached. This state is signaled by the level sensor system then causes the Ez1 valve to close.

3. The research object and methods

The research on the prototype cogeneration unit was carried out while fuelling the engine with NG and LPG. During the testing, the engine was driving a synchronous generator specified in section 2.1. The photos of selected elements tested prototype has been shown on Fig. 4.

1 – SI engine, **2** – Lubricating oil tank, **3** – Pressure reducer, **4** – Low temperature heat exchanger, **5** – High temperature heat exchanger, **6** – Control cabinet.

Fig. 4. Image of selected elements of the prototype

To provide an electrical load, the system had been connected to the power grid. Correct operation of the electric generator with a power grid was only possible at synchronous speed, i.e. 1500 rpm. When the ICE was operated at 1500 rpm with fitted factory flywheel, there were significant changes in the instantaneous angular velocity of the crankshaft. These changes caused the generator to fall out of synchronous speed. For this reason, an additional flywheel was designed and fitted to the engine crankshaft. This method ensured that the engine was able to run at the speed that the generator can work properly.

The heat generated by the system was transferred to the radiator with a variable cooling capacity. The electric power of the cogeneration system was modulated by changing the throttle position and/or gas fuel actuator thus influencing indirectly by increasing or decreasing the torque generated on the shaft of the engine.

The tests were carried out for an optimised value of ignition advance angle and two different mixture compositions. Therefore, results carried out for five different loads of the engine during the combustion of a stoichiometric mixture. In addition, tests were conducted for each of the five mentioned loads of the engine while burning a lean mixture (λ = 1.3). The CHP prototype operating points during the laboratory tests along with selected system operating parameters (average values maintained during test trials) are presented in table 3.

Table 3. CHP system prototype points during the tests and selected system operating parameters

Test trial	1	2	3	4	5
Engine speed, [rpm]	1500				
Electric output power [W], (±2%)	1000	2000	3000	4000	5000
Time of constant work for each trial, [h]	12	12	12	12	12
Air-fuel mixture temperature [°C], (±3°C)	35	35	35	35	35
Excess air ratio [-]*, (±0.02; 0.04)	1; 1.3	1; 1.3	1; 1.3	1; 1.3	1; 1.3
Engine oil sump temperature [°C], (±2°C)	80	82	83	85	85
Engine coolant temperature [°C], (±2°C)	82	84	85	87	87

* The test trial has been performed separately for each excess air ratios and fuel

During the experiment, the electric power was measured by the Fluke Norma 5000 power analyser. In turn, the mass stream of fuel consumed by the engine was measured using a Sartorius weight. Also, the composition of dry exhaust gases at the outlet of the engine was measured using the Capelec CAP 3000 flue gas analyser. The temperature at selected points in the system was measured using k-type thermocouples. The engine after treatment system has been equipped in three-way catalyst converter.

On the basis of the conducted research, the specific emission of exhaust compounds, electrical efficiency and total efficiency of the CHP system has been determined in a range of electrical power output changes.

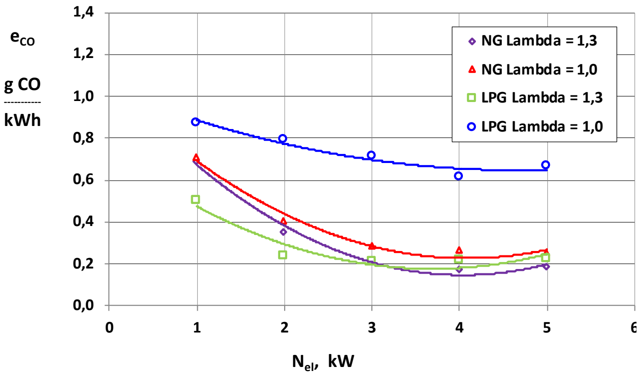


Fig. 5. Specific emission of CO vs mCHP unit output electric power

Figure 5 to 8 shows the influence of mCHP electric power output and ICE air excess ratio value on exhaust gas specific emissions. The specific emission is calculated to the value of electricity generated by the mCHP unit.

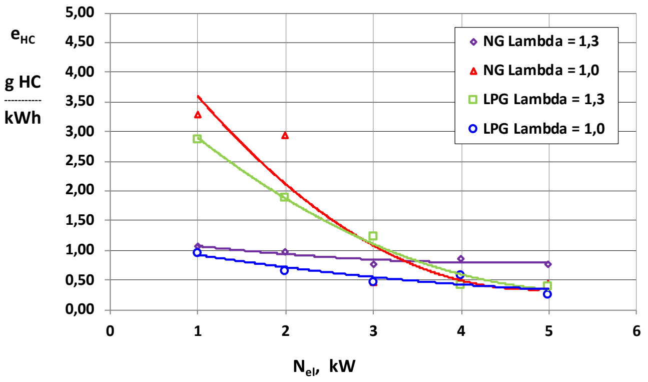


Fig. 6. Specific emission of HC vs mCHP unit output electric power

As can be seen in Figs 5 and 6, by increasing load, the unit value of CO and HC emissions decreases, which is caused by the higher temperature of the charge in the cylinder and favorable conditions for fuel oxidation.

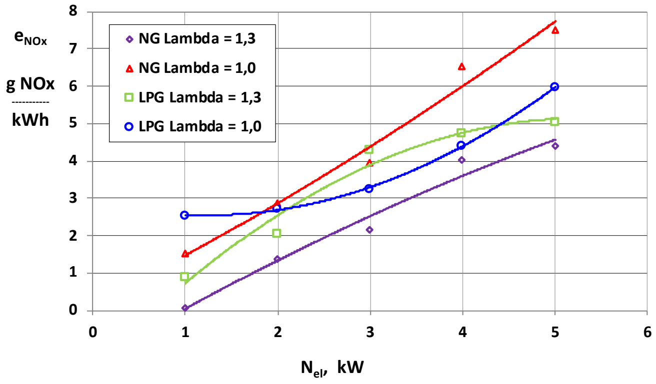


Fig. 7. Specific emission of NO_x vs mCHP unit output electric power

The specific NO_x emission (Fig. 7) increases with the increase in the load of the cogeneration system, which is related to the higher value of local temperature peaks in the combustion chamber. The main mechanism responsible for the formation of nitrogen oxides during combustion in an SI engine is the thermal mechanism.

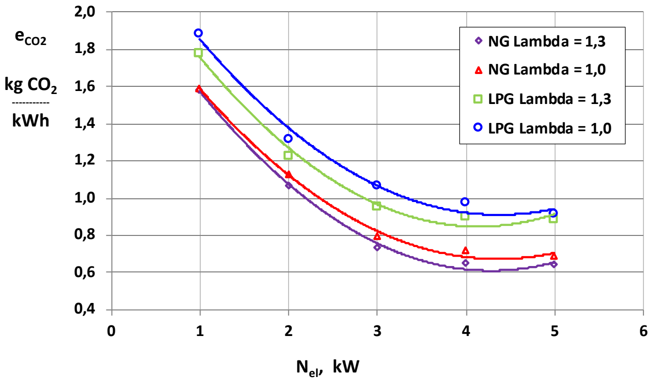


Fig. 8. Specific emission of CO2 vs mCHP unit output electric power

As can be seen in Fig. 8, the specific emission of CO_2 decreases with increasing load for both tested fuels, which is due to the fact that by increasing load of the engine, its energy efficiency increases, therefore the efficiency of electricity generation by the cogenerator (Fig. 9).

The obtained values of emission factors for harmful substances, the results of which are presented in Figs 5 to 8, confirm that the prototype cogeneration system meets the Stage II emission standard (in accordance with Directive 2002/08/EC) for small SI engines with a power below 19 kW. D2 ISO 8178.

Figure 9 shows the results of the electricity generation efficiency. The obtained results indicate that the applied method of internal combustion engine control (mixed qualitative and quantitative control) brings the expected results. The maximum efficiency of electric power when fueled by NG with the excess air ratio of λ = 1.3 is 30.7% and is higher than the value obtained for the same amount of the excess air ratio during LPG supply by 2.7 percentage points.

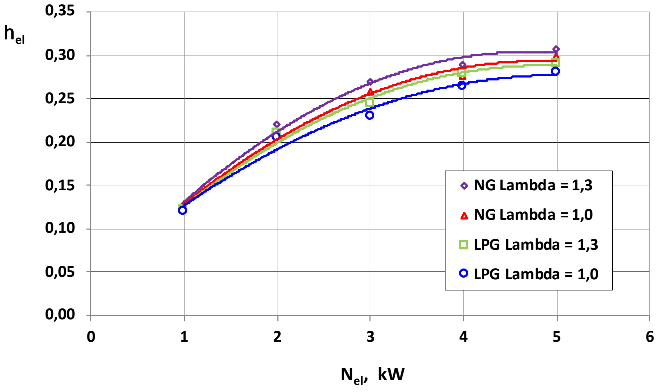


Fig. 9. Electrical efficiency of mCHP unit vs output electric power

Figure 10 shows the results of the total efficiency of the prototype for two products electricity and useful heat. The obtained results show that the applied method of controlling the allows to obtain the total efficiency of the cogeneration system at an average level of 91%.

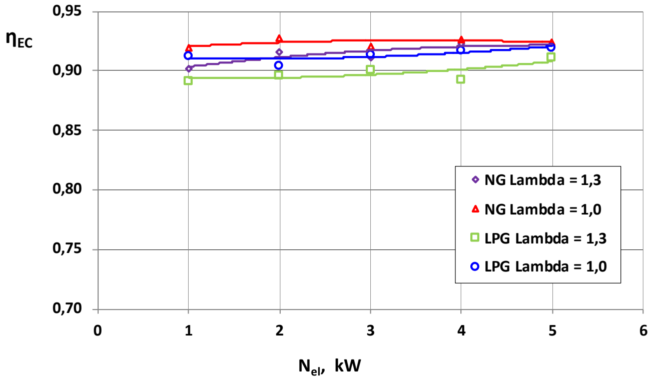


Fig. 10. Total efficiency of mCHP unit vs output electric power

It should be emphasized that the heat flux received from the system was determined in the conditions of periodic switching of heat reception, which led to fluctuations in the temperature difference at the inlet and outlet of the plate exchanger. In addition, depending on the capabilities of the reception system, i.e. in particular on the return temperature of the heat reception medium, it is possible to use an additional condensation exchanger, that will increase the efficiency of heat generation by the cogeneration system.

4. Conclusions

From the tests of the prototype micro cogeneration system based on SI engine and synchronous generator the following conclusions can be drawn:

1. For booth used fuels, the smooth work of prototype was possible during operation the SI engine with lean air fuel mixture and amount of air excess ratio up to 1.3. It is necessary to modify ether the engine combustion chamber or use spark plugs dedicated for lean combustion for leaner mixture necessary.
2. It was essential to use an additional flywheel for the engine to obtain the same synchronization of the electric generator with the power grid.
3. The maximum electricity generation efficiency for natural gas was more than 1 percentage point higher compare to LPG. The reason of it can be the low in-cylinder temperature using NG (for each of fuel the ignition timing has been optimised taking in to account the efficiency).
4. The exhaust gas emission level confirm that the prototype cogeneration system meets the Stage II emission standard (in accordance with Directive 2002/08/EC) for small SI engines with a power below 19 kW. D2 ISO 8178).
5. The lower value of CO2 emissions when the mCHP unit is fuelled with natural gas results from the lower content of the carbon in the fuel and due to the higher value of the engine efficiency achieved for natural gas.
6. The intake valve guides was the weakest part of the engine. After approximately 800 mth of prototype work under various load (1–6 kWel), there was a lubricating oil leak in to the combustion chamber on the valve guide of cylinder No. 2.

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Nomenclature

e_{CO}	specific emission of carbon monoxide
e_{HC}	specific emission of hydrocarbons
e_{NOx}	specific emission of nitrogen oxides
η_{el}	electrical efficiency of mCHP unit
η_{EC}	total efficiency of mCHP unit
LPG	liquified petrolum gas
NG	natural gas
SI	spark ignition
mCHP	micro Combined Heat and Power

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