Testing of the micro-cogenerator TOTEM 10 manufactured by TOTEM Energy

Steady state tests at diverse net electric powers and inlet temperatures of cogeneration water

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Abstract

The micro-cogenerator TOTEM 10 manufactured by TOTEM Energy S.r.l. is tested experimentally at the Laboratory of Micro-Cogeneration[1] of Politecnico di Milano to determine its electric and thermal performances under diverse working conditions. A working condition is a steady state operation defined by the controlled parameters: temperature of the ambient at 25°C mass flow rate of the cogeneration water at 1.11 kg s^{-1} (4.00 m^3 h^{-1}) and inlet temperature of the cogeneration water at alternatively 35 and 70°C, and net electric power at alternatively 5, 7.5 and 10 kW. Every working condition is verified repeatedly at least four times over at least two days. The thermodynamic models employed for determining the performances from the recorded data are based on the technical information by the U.S. National institute of Standards and Technology (NIST) and by the International Association for the Properties of Water and Steam (IAPWS). The data acquired during a single test are post-processed as follows. First, the averaged values of all measures for each working condition are evaluated. Then, the performances for each test are assessed and, simultaneously, the instrumental, combined and extended (coverage factor of 2) uncertainties are calculated by way of the standard ISO IEC GUIDE 98-3. Subsequently, all tests at each working condition are verified for compatibility applying statistical methods.

The main energy performances, referred to the Lower Heating Value (LHV) of the consumed natural gas, at the working conditions of all net electric powers and of the inlet temperature of the cogeneration water at 35 and 70°C, all expressed at a 95%-level of confidence, are:

Water inlet temperature (setpoint)		**35°C**	**35°C**	**35°C**	**70°C**	**70°C**	**70°C**
Net electric power (set point)		**5 kW**	**7.5 kW**	**10 kW**	**5 kW**	**7.5 kW**	**10 kW**
Number of *compatible* tests		4	4	4	4	5	4
Net electric power (measured)	kW	4.96 ±0.06	7.41 ±0.03	9.86 ±0.06	4.91 ±0.07	7.42 ±0.12	9.90 ±0.09
Thermal power	kW	16.4 ±0.2	20.3 ±0.2	24.93 ±0.09	14.03 ±0.16	17.8 ±0.3	21.4 ±0.3
Net electric efficiency (LHV)	-	0.2353 ±0.0015	0.2739 ±0.0010	0.295 ±0.003	0.2341 ±0.0008	0.2734 ±0.0012	0.2963 ±0.0015
Thermal efficiency (LHV)	-	0.779 ±0.007	0.752 ±0.010	0.747 ±0.004	0.669 ±0.004	0.655 ±0.003	0.64 ±0.003
Total efficiency (LHV)	-	1.015 ±0.008	1.026 ±0.010	1.042 ±0.006	0.903 ±0.005	0.928 ±0.003	0.936 ±0.004

[1] http://www.gecos.polimi.it/laboratories/micro-cogeneration.php

1 Introduction

TOTEM Energy S.r.l. and Politecnico di Milano are collaborating on a research program for testing, at both steady state and at cyclic or transient conditions, a number of micro-cogenerators manufactured by TOTEM in the Laboratory of Micro-Cogeneration at Politecnico. This laboratory is an infrastructure for testing in general cogeneration and trigeneration units fueled by natural gas, hydrogen, synthetic gas or any mixtures of the previous as well as for testing heat pumps, absorption chillers and boilers. Systems are characterized in terms of energy and environmental performances, allowing to improve if necessary physical components and control logics [1].

This work outlines the activities conducted specifically on the micro-cogenerator TOTEM 10, a unit capable of generating electrical power up to 10 kW, to determine its electric and thermal performances under diverse working conditions. A working condition, as defined here, is a steady state operation of the cogenerator identified by the following controlled parameters:

- temperature of the ambient air inside the laboratory at 25°C,
- mass flow rate of the cogeneration water at 1.11 kg s^{-1} (that is 4.00 m^3 h^{-1}),
- inlet temperature of the cogeneration water at alternatively 35 and 70°C,
- net electric power at alternatively 5, 7.5 and 10 kW.

In particular, the net electric power is imposed before each test defining properly the set point of the gross electric power, which is editable via the control panel of the cogenerator.

In order to verify the repeatability and to improve the confidence of the results, each working condition is replicated at least four times over at least two different days. During a single test at a given working condition, the following measurements are acquired (the underlined ones are also controlled as seen above):

- barometric pressure, <u>temperature</u> and relative humidity of the ambient air,
- mass flow rate, pressure, temperature and composition of the consumed natural gas,
- temperature of the exhaust gas,
- <u>mass flow rate</u>, pressure, pressure drop, <u>inlet temperature</u> and outlet temperature of cogen water,
- mass production of the condensate water over time,
- current, tension, power factor, electric power of each electric phase and <u>net electric power</u>.

Figure 1 visualizes TOTEM 10 installed inside the laboratory, while Table 1 reports the characteristics of the adopted instrumentation in terms of manufacturer, model and uncertainty.

Figure 1. TOTEM 10 under testing in the Laboratory of Micro-Cogeneration at Politecnico di Milano.

Table 1. Type and characteristics (manufacturer, model and uncertainty) of the adopted instrumentations (F.S. stands for full scale, R.V for read value).

Parameter	Unit	Instrument	Uncertainty
Ambient barometric pressure	hPa	Vaisala PTU300	±0,15 hPa
Ambient temperature	°C	Vaisala PTU300	±0,10 °C
Ambient relative humidity	%	Vaisala PTU300	±0,6%R @0-40%RH, ±1,0%RH@40-97%RH
Natural gas pressure	mbar	Bronkhorst IN-PRESS P-502CI	±(0,5%F.S.)
Natural gas temperature	°C	TC Direct Pt100 class 1/10 DIN	±(0,03+0,05/100*|T|)
Natural gas flow rate	$Nm^3\ h^{-1}$	Bronkhorst IN-FLOW F-106BZ	±1%F.S.
Natural gas composition	%	Pollution micro gas chromatographer	2,00% su gas taratura
Exhaust gas temperature	°C	TC Direct Pt100 class 1/10 DIN	±(0,03+0,05/100*|T|)
Water pressure	bar_A	Rosmount 2088 Pressure Trasmitter	±0,1 span
Water pressure loss	bar	Rosemount 2051CF	±(0,075%F.S.)
Water mass flow rate	$kg\ s^{-1}$	Micromotion Coriolis Elite CMF100	±(0,03%R.V.)
Water inlet temperature	°C	TC Direct Pt100 class 1/10 DIN	±(0,03+0,05/100*|T|)
Water outlet temperature	°C	TC Direct Pt100 class 1/10 DIN	±(0,03+0,05/100*|T|)
Condensate mass over time	kg	Laumas elettronica TLS 420	±1g
Electric phase 1	W	Fluke Norma 4000	±0,1%R.V.
Electric phase 2	W	Fluke Norma 4000	±0,1%R.V.
Electric phase 3	W	Fluke Norma 4000	±0,1%R.V.

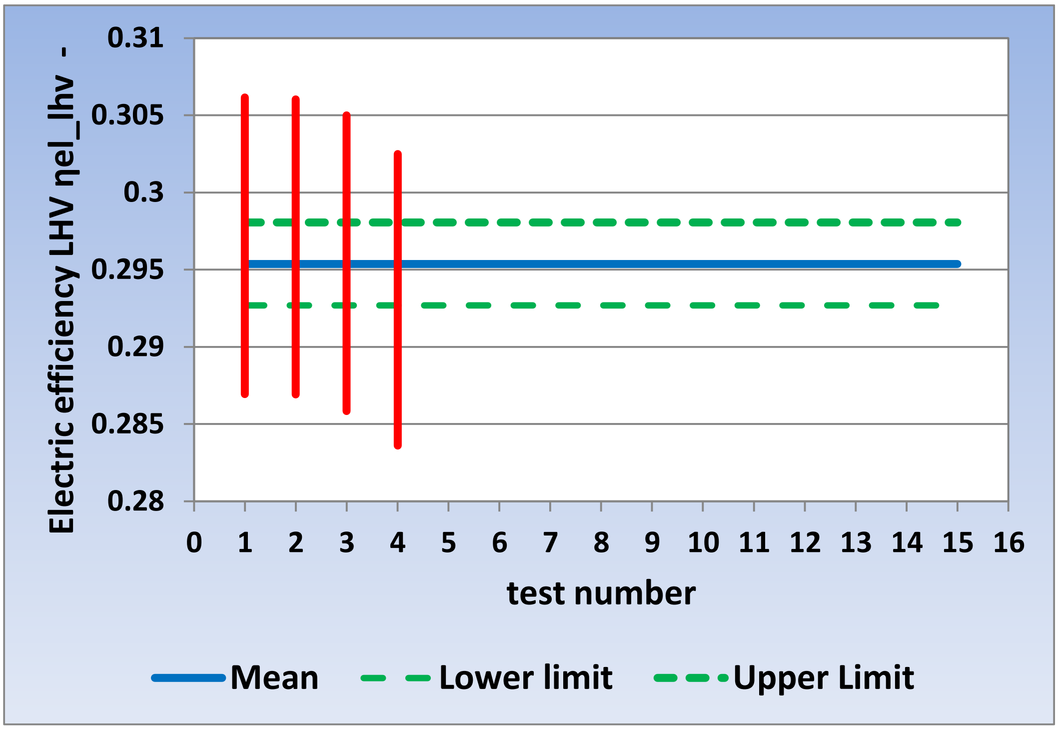
2 Experimentation

The micro-cogenerator TOTEM 10 is installed inside the laboratory in the same manner as it would be installed at any end-user. The experimental protocol comprises: launching the laboratory systems, setting the parameters for the desired working condition via both the lab control system and the unit control panel, and starting the cogenerator. The steady state operation is reached when the inlet and the outlet temperatures of the cogenerator water as well as the temperature of exhaust gas vary within ±0.5°C. Once steadiness is achieved, data acquisition starts. Natural gas compositions are recorded every about 3 minutes, while all other measurements every 2 seconds. A measurement of the natural gas composition, by way of gas chromatography, is accepted if the sum of the resulting molar fractions falls between 0.98 and 1.02. The test ends when at least three readings of the natural gas composition are accepted and when, if exhaust water condenses, at least 100 g of condensate water are collected. Typically, tests last between 10 to 20 minutes. As anticipated, in order to verify the measurement repeatability and improve the result confidence, a working condition is replicated at least four times over at least two different days.

At the end of a test, the average values of all measurements are computed over the test period. From the averaged values, mass and energy flows are reconstructed adopting conventional thermodynamic relations. Among them, the properties of natural gas are computed from the Shomate equation provided by the U.S. National Institute of Standards and Technology (NIST) [2], while those of water from the routines by the International Association for the Properties of Water and Steam (IAPWS) [3]. The computed Lower and Higher Heating Values (LHV and HHV) from NIST equations turn out to be in very strict agreement with the standard ISO 6976 [4]. Moreover, the molar flow rate of natural gas is corrected for the variable composition with the procedure defined by the manufacturer [5]. Ultimately, net electric and thermal efficiencies of the test can be calculated with respect to LHV and HHV. Simultaneously, instrument, combined and extended (coverage factor of 2) uncertainties are computed accordingly to ISO IEC GUIDE 98-3 [6].

Because tests for each working condition are replicated, there are diverse averages and performances for a condition (for instance, if there are five tests for a condition, there are five net electric and thermal powers as well as five net electric and thermal efficiencies). Hence, tests are verified for *compatibility*. The compatibility verification requires, in sequence, to plot selected properties for all tests at a given working condition showing the extended uncertainty intervals about those properties. Then, the mean values and the standard deviations of the properties are computed; from these summary statistics, assuming a Student’s t-distribution of the properties, the confidence intervals at a desired confidence level are plot about the mean values. A test for a working condition is *compatible* with all other tests for the same working condition if its extended uncertainty interval overlaps with the confidence interval for all the selected properties. The selected properties for the compatibility verification are: heat input rate, net electrical power, thermal power, net electric efficiency and thermal efficiency. The adopted confidence level is 95%.

For sake of clarity, Figure 2 shows the compatibility verification of the test at the working condition of the net electric power at 10 kW and the inlet temperature of the cogeneration water at 35°C for two selected properties: the net electric efficiency (top) and the thermal efficiency (bottom), both with respect to LHV.



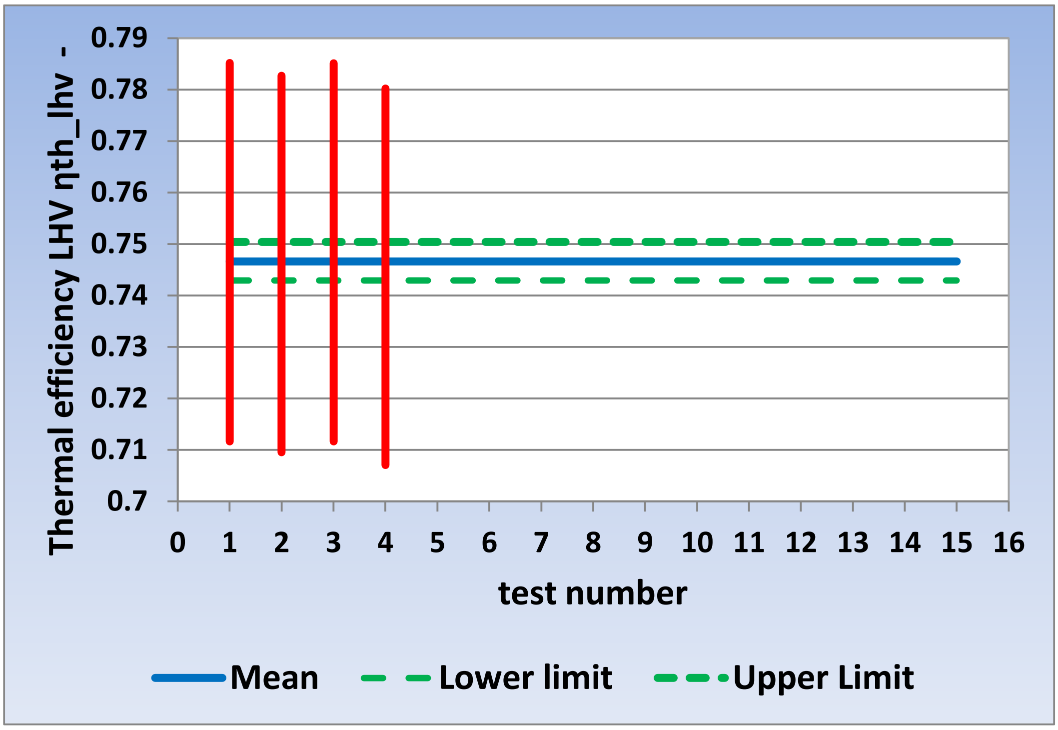


Figure 2. Compatibility verification of the tests at 10 kW electric load and 35°C water inlet for the net electric efficiency (top) and the thermal efficiency (bottom), both with respect to LHV.

3 Results

Based on the methodology outlined previously, the experimental results from the campaign on the micro-cogenerator TOTEM 10 are reported in this section. Table 2 shows the mean values and the 95%-confidence intervals of the main parameters at the working conditions of all net electric powers and all inlet temperatures of the cogeneration water. All tests executed for each working condition have been verified to be compatible.

Table 2. Mean values and 95%-confidence interval of the main parameters at the working conditions of all net electric powers and of all inlet temperatures.

Water inlet temperature (setpoint)		**35°C**	**35°C**	**35°C**	**70°C**	**70°C**	**70°C**
Net electrical power (setpoint)		**5 kW**	**7.5 kW**	**10 kW**	**5 kW**	**7.5 kW**	**10 kW**
Number of *compatible* tests		4	4	4	4	5	4
Cogeneration inlet	Unit						
Natural gas flow rate	Nl min^{-1}	34.5 ±0.4	44.33 ±0.12	54.7 ±0.2	34.3 ±0.4	44.5 ±0.6	54.8 ±0.9
"	Nm^3 h^{-1}	2.07 ±0.02	2.66 ±0.007	3.281 ±0.012	2.06 ±0.02	2.67 ±0.03	3.29 ±0.05
Nat. gas Lower Heating Value	kJ mol^{-1}	821.2 ±1.0	821.3 ±1.5	821 ±3	821.5 ±0.6	820.4 ±1.3	819 ±4
"	MJ kg^{-1}	47.5 ±0.3	47.49 ±0.19	47.6 ±0.2	47.62 ±0.03	47.62 ±0.16	47.4 ±0.9
"	kWh Nm^{-3}	10.177 ±0.013	10.178 ±0.019	10.18 ±0.03	10.181 ±0.007	10.167 ±0.016	10.15 ±0.05
Nat. gas Higher Heating Value	kJ mol^{-1}	909.8 ±1.2	909.8 ±1.7	910 ±3	910.1 ±0.6	908.9 ±1.4	908 ±4
"	MJ kg^{-1}	52.6 ±0.3	52.6 ±0.2	52.7 ±0.3	52.76 ±0.03	52.76 ±0.18	52.6 ±1.0
"	kWh Nm^{-3}	11.275 ±0.015	11.276 ±0.021	11.27 ±0.04	11.279 ±0.007	11.264 ±0.017	11.25 ±0.05
Heat input rate (LHV)	kW	21.1 ±0.3	27.07 ±0.06	33.39 ±0.10	21.0 ±0.3	27.1 ±0.3	33.4 ±0.4
Heat input rate (HHV)	kW	23.3 ±0.3	29.99 ±0.06	36.99 ±0.11	23.2 ±0.3	30.1 ±0.4	37.0 ±0.4
Cogen water flow rate	kg s^{-1}	1.113 ±0.013	1.111 ±0.016	1.109 ±0.006	1.111 ±0.003	1.114 ±0.003	1.1126 ±0.0017
Cogen water inlet temp. (meas.)	°C	34.976 ±0.008	34.975 ±0.012	34.979 ±0.010	70.032 ±0.016	70.025±0.008	70.02 ±0.08
Cogeneration outlet	Unit						
Net electrical power (measured)	kW	4.96 ±0.06	7.41 ±0.03	9.86 ±0.06	4.91 ±0.07	7.42 ±0.12	9.90 ±0.09
Cogen water outlet temp.	°C	38.51 ±0.07	39.36 ±0.06	40.36 ±0.03	73.05 ±0.03	73.84 ±0.05	74.61 ±0.06
Cogen water pressure drop	bar	266 ±6	265 ±7	264 ±3	256.5 ±1.5	257.8 ±1.7	257.4 ±1.1
Thermal power	kW	16.4 ±0.2	20.3 ±0.2	24.93 ±0.09	14.03 ±0.16	17.8 ±0.3	21.4 ±0.3
Condensate mass flow rate	kg h^{-1}	0.888 ±0.004	1.134 ±0.015	1.37 ±0.06	0	0	0
Energy performances							
Net electrical efficiency (LHV)	-	0.2353 ±0.0015	0.2739 ±0.0010	0.295 ±0.003	0.2341 ±0.0008	0.2734 ±0.0012	0.2963 ±0.0015
Net electrical efficiency (HHV)	-	0.2124 ±0.0014	0.2472 ±0.0009	0.267 ±0.002	0.2113 ±0.0007	0.2468 ±0.0011	0.2674 ±0.0014
Thermal efficiency (LHV)	-	0.779 ±0.007	0.752 ±0.010	0.747 ±0.004	0.669 ±0.004	0.655 ±0.003	0.64 ±0.003
Thermal efficiency (HHV)	-	0.703 ±0.006	0.679 ±0.009	0.674 ±0.003	0.604 ±0.004	0.591 ±0.002	0.578 ±0.003
Total efficiency (LHV)	-	1.015 ±0.008	1.026 ±0.010	1.042 ±0.006	0.903 ±0.005	0.928 ±0.003	0.936 ±0.004
Total efficiency (HHV)	-	0.916 ±0.007	0.926 ±0.009	0.941 ±0.006	0.815 ±0.004	0.838 ±0.002	0.845 ±0.003

The electric consumption of the auxiliaries is not measured during the tests, but it is approximated as the measured electric consumption of the cogenerator in the minutes following a shut-down. Consequently, gross electric power and efficiency for all tests can be estimated as reported in Table 3. Given the estimation procedure, the uncertainty on the gross power and efficiency cannot be quantified appropriately.

Table 3. Estimated gross electrical power and efficiencies at the working conditions of all net electric powers and of all inlet temperatures.

Water inlet temperature (setpoint)		**35°C**	**35°C**	**35°C**	**70°C**	**70°C**	**70°C**
Net electrical power (setpoint)		**5 kW**	**7.5 kW**	**10 kW**	**5 kW**	**7.5 kW**	**10 kW**
Auxiliary electric consumption	kW	0.195	0.195	0.195	0.195	0.195	0.195
Gross electric power	kW	5.16	7.61	10.06	5.11	7.62	10.10
Gross electric efficiency (LHV)	-	0.2443	0.2809	0.3011	0.2431	0.2810	0.3022

4 Conclusions

A micro-cogenerator TOTEM 10 manufactured by TOTEM Energy has been tested experimentally at the Laboratory of Micro-Cogeneration of Politecnico di Milano to determine its energy performances under diverse working conditions. A working condition is defined by the controlled parameters: temperature of the ambient air at 25°C; mass flow rate of the cogeneration water at 1.11 kg s^{-1} (that is 4.00 m^3 h^{-1}) and inlet temperature of the cogeneration water at alternatively 35 and 70°C; net electric power at alternatively 5, 7.5 and 10 kW. Every working condition has been verified repeatedly at least four times over at least two different days. Tests have been carried out positively versus all the assumed working conditions, deriving the energy performances reported in Table 2.

5 Bibliography

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