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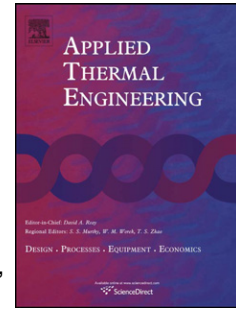
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**Use of a test-bed to study the performance of micro gas turbines  
for cogeneration applications**

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1 **Abstract**

2

3 This paper presents the experimental results of a test-bed developed to analyze a 100 kW cogeneration micro gas  
4 turbine (MGT). Its main feature, flexibility, allows MGT testing in nearly all the conditions that final use may  
5 entail, in particular simulation of operating conditions and thermal loads in broadly different electrical power,  
6 flow rate and temperature conditions of the cogeneration circuit. The MGT and its operating modes are described  
7 and the test-bed design philosophy is outlined. Finally the methods applied to test the cogeneration plant's  
8 performance are described and the experimental results in terms of power, efficiency, primary energy saving  
9 (*PES*) index and emissions are reported.

10 In the tests electrical power ranged between 40 and 100 kW; electrical efficiency reached ~ 29 % in the 80-100  
11 kW range. Analysis of the performance of the recovery heat exchanger at different values of inlet and outlet  
12 water temperature and flow rate showed that the maximum thermal power recovered was ~ 160 kW and the  
13 maximum *PES* index was about 24 %. With regard to the main pollutants at the exhaust, NO<sub>x</sub> concentrations  
14 were < 6 ppmv in the whole MGT working range, while CO concentrations increased substantially at low  
15 electrical power values, starting from around 10 ppmv at nominal load.

16

17 **Keywords:** micro gas turbine, cogeneration, test-bed, thermal recovery, electrical performance, primary energy  
18 saving

19

20 **1. Introduction**

21

22 In conventional energy systems electrical power is conveyed from large-scale plants located far away from the  
23 region where it is used, while energy for heating is supplied separately as fuel on a local basis. In the future  
24 distributed energy networks are likely to provide both electrical and heating energy through CHP plants built  
25 close to the consuming region [1, 2]. The value of MGTs as components of distributed energy systems lies in  
26 their low environmental impact in terms of pollutants. MGTs appear to be particularly well suited for service  
27 sector, household and small industrial applications [3, 4, 5, 6].

28 Despite this, the market for MGTs is still modest; research is therefore being conducted to make them more  
29 appealing through application of concepts such as trigeneration [7, 8, 9], inlet air cooling [9, 10, 11], biogas use  
30 [12, 13] or combinations thereof [14]. Some authors have also studied the possibility of enhancing performances  
31 by adding a bottoming organic Rankine cycle to recover the thermal power of exhaust gases [15, 16].

32 The majority of the relevant works on MGT cogeneration units report operation and emissions data at nominal  
33 load in ISO conditions [17]. Most of these data are taken directly from the manufacturer's documentation,  
34 whereas few studies have assessed non-nominal and/or partial load conditions. For example, Colombo et al. [18]  
35 describe a cogeneration test-bed and the performance and pollutant emissions of a 100 kW MGT at partial load  
36 using a set outlet temperature of the heat recovery boiler water. Fairchild et al. [19] report the experimental  
37 results of a 30 kW cogeneration MGT, also running at partial load, focusing on the influence of backpressure on  
38 performance; however, their thermal performance data are not for the turbine, but for the whole HVAC system at  
39 the site where it is installed.

40 The present paper describes MGT performance in partial electrical and thermal load conditions, providing  
41 experimental data from an ad hoc test-bed.

42

### 43 **Nomenclature**

44

45 CHP combined heat and power

46  $c_w$  average specific heat of the water inside the RHE (kJ/kg K)

47 HVAC heating, ventilation and air conditioning

48  $LHV$  natural gas lower heating value (kJ/kg)

49  $\dot{m}_f$  natural gas mass flow rate (kg/h)

50 MGT micro gas turbine

51  $P_e$  electrical power (kW)

52	$PES$	primary energy saving
53	$P_{th}$	thermal power (kW)
54	$P_{th}^0$	thermal power with the bypass valve in fully closed position (kW)
55	$PTH\%$	percent thermal power recovered
56	$Q_w$	volumetric flow rate of the water in the primary circuit (l/s, l/min)
57	RHE	recovery heat exchanger
58	$T_{w\_in}$	RHE water inlet temperature (°C)
59	$T_{w\_out}$	RHE water outlet temperature (°C)
60	$\eta_e$	electrical efficiency
61	$\eta_{e\_ref}$	separate generation system reference electrical efficiency
62	$\eta_{th}$	thermal efficiency
63	$\eta_{th\_ref}$	separate generation system reference thermal efficiency
64	$\eta_{tot}$	total efficiency
65	$\rho_w$	density of the water in the primary circuit at the RHE inlet (kg/m <sup>3</sup> )

66

## 67 2. The cogeneration micro gas turbine

68

69 The machine chosen for the tests was a Turbec T100 PH cogeneration MGT based on a regenerative Brayton  
 70 cycle; it is a more recent version of the one investigated by Colombo et al. [18] and features an embedded fuel  
 71 compressor. The unit is fired with natural gas and the combustor, a lean-premixed-low-emission type, guarantees  
 72 volumetric concentrations of NO<sub>x</sub> and CO < 15 ppmv at 15% O<sub>2</sub> at full load.

73 In ISO 2314 [17] conditions the machine produces 100 kW of electrical power with an efficiency of 30%; the  
 74 combustion products exit the turbine at a temperature of 645 °C, cross the regenerator and enter the recovery  
 75 heat exchanger at 270 °C. The RHE is a counter-flow type designed for a water mass flow rate of 2 l/s and  
 76 temperatures of 50 °C and 70 °C at the inlet (to avoid dew condensation in the worst foreseeable conditions) and  
 77 outlet, respectively. At these nominal conditions stated thermal power production is ~ 155 kW, with a thermal  
 78 efficiency of 47 %.

79 An electrically driven bypass valve fitted along the RHE inlet manifold can divert some of the exhaust gases to  
 80 the chimney, to regulate the thermal power recovered.

81 The MGT performance data as supplied by the manufacturer are summarized in Table 1.

82 In practice, demand is represented by user-set values of electrical power and fluid temperature at the RHE outlet,  
83 and by selection of the operating mode (electrical or thermal priority).

84 In the electrical priority mode the MGT produces the electrical power required by the user and the fluid  
85 temperature is kept at the set-point through regulation of bypass valve opening.

86 In the thermal priority mode the bypass valve is completely closed and all the exhausts pass through the RHE to  
87 produce thermal power. The temperature of the hot fluid is kept at its set-point by variations in the amount of  
88 electricity produced; the user-selected electrical power value is the threshold.

89 Electrical priority mode operation with the bypass valve completely closed is equivalent to operation in the  
90 thermal priority mode.

91

### 92 **3. Test-bed**

93

94 The test-bed, illustrated in figure 1, was designed to simulate a broad range of thermal demands and is therefore  
95 capable of testing the cogeneration system in a wide range of user-selected conditions, involving several  
96 combinations of electrical power, water flow rate and operating temperatures.

97 The test-bed consists of four main subsystems: the *natural gas feeding plant*, the *inlet and extraction manifold*,  
98 the *grid connection interface*, and the *hydraulic system for thermal power dissipation*.

99 The main components of the *natural gas feeding plant* are a valve that reduces the grid pressure to the required  
100 turbine inlet value and a fuel flow meter measuring the natural gas mass flow rate.

101 The *inlet and extraction manifold* consists of three ducts and a centrifugal extractor fan. One duct provides inlet  
102 air that serves both as a working fluid in the turbo compressor and as a coolant for the auxiliary system; the other  
103 two ducts collect cooling air from the turbine enclosure and the exhausts at the RHE outlet. All ducts are fitted  
104 with thermocouples; a gas analyzer for emission control is installed in the exhaust gas duct.

105 The *grid connection interface* manages the parallel connection with the grid and measures the electrical power  
106 produced. Its main components are a safety switch, to disconnect the turbine from the grid in case of emergency,  
107 and a grid analyzer to measure electrical parameters and power production.

108 The *hydraulic system for thermal power dissipation* is the most complex part of the test-bed. It consists of two  
109 separate circuits thermally interconnected by a plate heat exchanger. The primary circuit contains the water  
110 circulating through the turbine RHE, while the secondary circuit contains a water-glycol mixture that discharges  
111 the heat to the outside air by circulating through an air cooler.

112 The water circuit is provided with a volumetric flow meter and with two Pt100 temperature sensors at the RHE  
113 inlet and outlet.

114 Valves V1 and V2 in the water circuit allow flow rate regulation through the RHE. V1 is only manually  
115 operated, whereas V2—which keeps the water temperature at the RHE outlet at its set-point—can also be  
116 controlled remotely by a PID.

117 The pneumatic mixing valve V3, installed in the secondary circuit to keep the water temperature at the RHE inlet  
118 at its set-point, is automatically driven by a PID controller.

119 All measurement instruments and control signals are managed by means of a PLC connected to a PC.

120 The measurement devices installed and their accuracy are listed in Table 2.

121

#### 122 **4. Evaluation of micro gas turbine performance: results and comments**

123

124 The test-bed's characteristics make it possible to assess the electrical and thermal performance of the  
125 cogeneration unit in various working conditions, including electrical power settings ranging from minimum to  
126 nominal value and thermal power settings ranging from the thermal priority mode maximum to the electrical  
127 priority mode minimum. Given the dependence of MGT performance on ambient temperature [20], only  
128 experimental data acquired at nearly constant ambient temperature (from 5 to 10 °C) were considered.

129 First of all, the tests were carried out with the water volumetric flow rate and the inlet temperature in the primary  
130 circuit at nominal values (2 l/s and 50 °C, respectively), using several different combinations of electrical power  
131 and degree of bypass valve opening (from fully open to fully closed).

132 These data, reported in section 4.1, were used to draw up a performance chart of the cogeneration unit in the 40-  
133 100 kW electrical power range.

134 Since the MGT can be fed water at non-nominal conditions, depending on user requirements, additional tests  
135 were carried out with different water flow rates and/or operating water temperatures. These data are reported in  
136 sections 4.2 and 4.3.

137 For each working point the thermal power recovered and the electrical, thermal and total efficiency of the unit  
138 were calculated as:

$$139 \quad P_{th} = \rho_w Q_w c_w (T_{w_{out}} - T_{w_{in}}) \quad 1)$$

$$140 \quad \eta_e = \frac{P_e}{\dot{m}_f LHV} \quad 2)$$

$$141 \quad \eta_{th} = \frac{P_{th}}{\dot{m}_f LHV} \quad 3)$$

$$142 \quad \eta_{tot} = \frac{P_e + P_{th}}{\dot{m}_f LHV} = \eta_e + \eta_{th} \quad 4)$$

143

#### 144 4.1. Cogenerator performance at nominal inlet thermal conditions

145

146 Figure 2 reports the cogenerator's electrical and thermal performances obtained at different power settings  
 147 between 40 and 100 kW (using 20 kW steps) with constant water volumetric flow rate and inlet temperature in  
 148 the primary circuit (2 l/s and 50 °C, respectively).

149 At each given electrical power setting, the thermal power produced was highest with the machine working in  
 150 thermal priority mode. When the machine was switched to the electrical priority mode, opening of the bypass  
 151 valve reduced the water temperature at the RHE outlet, hence the thermal power recovered. Tests were carried  
 152 out with the bypass valve in 1/3, 2/3 and fully open positions.

153 The dotted lines in figure 2 join the points sharing the same percent thermal power recovered (*PTH%*):

$$154 \quad PTH\% = 100 \cdot \frac{P_{th}(P_e)}{P_{th}^0(P_e)} \quad 5)$$

155 where  $P_{th}^0(P_e)$  is the thermal power produced at an electrical power setting equal to  $P_e$  with a fully closed  
 156 bypass valve, i.e. the maximum  $P_{th}$  for that  $P_e$ .

157 Notably, the points corresponding to the same valve position fall nearly on the same *PTH%* curve regardless of  
 158 the electrical power setting.

159 The thermal power recovered did not decrease linearly with the degree of bypass valve opening. With the valve  
 160 1/3 open the *PTH%* was about 45 %, at 2/3 it was ~25 %, and even with the bypass valve fully open, a minimum  
 161 amount of exhausts still passed through the RHE, transferring about 15 % of the maximum thermal power to the  
 162 water.

163 This suggests the need for installing a heat dissipator in real applications, to prevent water boiling in the RHE in  
 164 the event of the thermal demand falling under the fully-open lower limit (*PTH%* < 15 %). When the turbine is  
 165 used only as an electrical generator for an extended period of time, the RHE should be drained.



166 The total efficiency data are reported in the performance chart next to each experimental point; the  
167 corresponding outlet temperature,  $T_{w,out}$ , can be read on the secondary axis on the right.  
168 The total efficiency data are also reported in figure 3 with the electrical efficiency data. For each working point,  
169 thermal efficiency is the difference between total and electrical efficiency.  
170 The average electrical efficiency is 28.5 % at maximum load, peaking at about 29.5 % for a net electrical power  
171 of 80 kW. Furthermore, efficiency declines to an average of 23.5 % at 40 kW. Taking into account inlet and  
172 exhaust duct pressure losses, these values are consistent with those stated in the manufacturer's data sheet [17].  
173 Figure 3 shows that the electrical efficiency does not depend on the position of the bypass valve (i.e. on  
174 operating mode); rather, for each electrical power setting the lower the thermal power demand (i.e. the greater  
175 the bypass valve opening), the lower the thermal efficiency (and thus total efficiency). For example, at 100 kW  
176 of electrical power, total efficiency is 74 % with the valve fully closed (thermal priority) and 36 % with the valve  
177 fully open (see also the data in figure 2).  
178 At the same time, for a given level of thermal power demand the greater the electrical power produced, the lower  
179 total efficiency. For example, it can be seen from figure 2 that the unit produces about 80 kW of thermal power  
180 either working in thermal priority mode, at 40 kW of electrical power, or working in electrical priority mode, at  
181 100 kW of electrical power with the bypass valve about 1/3 open. In the former case total efficiency is around 74  
182 %, in the latter it is slightly more than 51 %.  
183 Finally the concentrations of the primary pollutants [21] at 15 % O<sub>2</sub> dilution are reported in the performance  
184 chart. NO<sub>x</sub> were low in the whole electrical working range of the MGT, with a peak of ~6 ppmv in  
185 correspondence with the machine's minimum load; CO concentrations < 10 ppmv were measured at 100 and 80  
186 kW, while at lower electrical power settings concentrations were significantly higher, with a maximum of 1550  
187 ppmv at 40 kW.

188

#### 189 *4.2. Cogenerator performance at nominal electrical power*

190

191 In this section the data show how water parameters at the RHE influence the recoverable thermal power when  
192 the system is working with the bypass valve fully closed (i.e. in thermal priority mode).

193 For each electrical power setting, the recoverable thermal power depends on the water parameters, because

194 whereas modification of inlet water parameters does not change the temperature and amount of the exhausts

195 entering the RHE, it does alter the outlet temperature of both water and exhausts, hence the mean temperature  
196 difference between the two fluids.

197 Here we focus on the 100 kW nominal electrical power point; the next section addresses lower power values.

198 Two experimental data sets are compared in figure 4, one regarding the RHE fed with the nominal mass flow  
199 rate of water at different temperatures and the other regarding the RHE fed with different mass flow rates at the  
200 nominal inlet temperature. The parameters (thermal power recovered, mass flow rate and inlet temperature) are  
201 reported as a function of outlet temperature.

202 As shown by the tendency lines, the data sets of the two cases (represented respectively as circles and squares in  
203 figure 4) converge at the nominal thermal values of  $Q_w = 2$  l/s,  $T_{w\_in} = 50$  °C, and  $T_{w\_out} = 70$  °C.

204 From this point, if the water temperature at the outlet is increased from the nominal value, the inlet temperature  
205 is kept constant at 50 °C, and the mass flow rate is reduced accordingly (squares), more thermal power is  
206 recovered with respect to the other case (circles).

207 Alternatively, if the water outlet temperature is increased from the nominal value, keeping the mass flow rate  
208 constant at 2 l/s, the inlet temperature rises accordingly (circles); as a result the mean temperature difference  
209 between the MGT exhausts and the water is lower than in the previous case and less thermal power is recovered.

210

#### 211 *4.3. Cogenerator performance at nominal water inlet and outlet temperatures*

212

213 In this section the data show how water conditions influence the thermal priority tendency lines.

214 Figure 5 reports the data obtained with water fed at the nominal inlet temperature (50 °C) with a constant  
215 temperature of 70 °C set at the RHE outlet. Starting from  $P_e = 100$  kW and nominal thermal conditions, the  
216 electrical power was reduced to 70 kW (by 5 kW steps) and the water mass flow passing through the RHE was  
217 reduced accordingly. The data used in figure 2 are also reported, to allow direct comparison.

218 The data of the two cases converge at the nominal values. Starting from the nominal point, if the electrical power

219 is reduced while keeping the inlet and outlet temperature at 50 °C and 70 °C, respectively (squares in figure 5),

220 less thermal power is recovered with respect to the other case (circles). Alternatively, if the electrical power is

221 reduced while keeping the mass flow rate constant at 2 l/s and the inlet temperature at 50 °C (circles), the

222 temperature at the RHE outlet decreases; the mean temperature difference between the MGT exhausts and water

223 is greater than in the previous case, and more thermal power is recovered accordingly.

224

225 **5. Primary energy saving**

226

227 To complete the analysis of the cogeneration unit this section reports some data relating to the comparison with a  
228 conventional separate generation system, which are useful to evaluate the practical use of the cogeneration unit.

229 From the energy point of view, this is done through the *PES* index, which quantifies the amount of primary  
230 energy that can be saved by heat and power cogeneration compared with separate generation, as:

$$231 \quad PES = 1 - \frac{I}{\frac{\eta_e}{\eta_{e\_ref}} + \frac{\eta_{th}}{\eta_{th\_ref}}} \quad (6)$$

232 where  $\eta_{e\_ref}$  and  $\eta_{th\_ref}$  are the reference electrical and thermal efficiencies of the separate generation systems.

233 If these are assumed to be  $\eta_{e\_ref} = 40\%$  and  $\eta_{th\_ref} = 80\%$  respectively, as prescribed by the Italian Authority for  
234 Electrical Energy and Gas, the MGT cogenerator guarantees values of the *PES* index between 0.19 and 0.23  
235 when working in thermal priority mode (bypass valve fully closed; see figure 6). Nearly all the working points in  
236 the electrical priority mode fall in the negative *PES* area, since the greater the bypass valve opening the lower the  
237 *PES*, i.e. more primary energy is consumed by the cogenerator than by the separate generation systems.

238

239 **6. Conclusions**

240

241 This paper reports the experimental results of a 100 kW cogeneration MGT obtained with a test-bed designed to  
242 simulate a broad range of operating conditions including partial electrical and thermal loads.

243 The main performance parameters of the cogenerator are first reported on a single chart drawn up for the  
244 nominal thermal conditions; the emissions data are reported as tables.

245 Some working points at non-nominal conditions are then analyzed, both to highlight the test-bed capabilities and  
246 to provide insights into and information on the MGT working modes.

247 Analysis of different electrical power settings between 40 and 100 kW yielded a maximum electrical efficiency  
248 of  $\sim 29.5\%$  at 80 kW and a minimum of  $\sim 23.5\%$  at 40 kW.

249 As regards pollutants,  $\text{NO}_x$  concentrations were very low in all working conditions, while CO concentrations  
250 were low at high-medium power and rose steeply at lower loads.

251 The tests showed heat priority operation to be the most efficient mode, as reflected both in total efficiency and in  
252 *PES* index values, and cogeneration with electrical priority to be the least efficient mode, due to bypass valve

253 opening, hence to the amount of heat discharged. A negative *PES* was actually found in a number of conditions  
254 with the bypass valve not closed, demonstrating that the electrical priority mode may be less efficient than  
255 separate production. The maximum thermal power recovered was about 160 kW, with a thermal and a total  
256 efficiency around 44 % and 74 %, respectively.

257 When the cogenerator was compared with standard separate production with  $\eta_{e\_ref}= 40\%$  and  $\eta_{th\_ref}= 80\%$  the  
258 maximum *PES* index was about 0.23.

259

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265

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308 9780750679695.ook of Air, Land and Sea Applications. ISBN-13: 9780750679695.

309 **Table captions**

310 Table 1. Micro gas turbine performance in nominal conditions<sup>a</sup>

311 Table 2. Measurement instruments

312

313 **Figure captions**

314 Figure 1. Layout of the MGT cogeneration test-bed

315 Figure 2. MGT performance chart in nominal inlet thermal conditions

316 Figure 3. Electrical and total efficiency in nominal inlet thermal conditions

317 Figure 4. MGT thermal performance at nominal electrical power

318 Figure 5. MGT performance at nominal water inlet and outlet temperatures

319 Figure 6. *PES* index value of the MGT cogeneration plant;  $\eta_{e\_ref} = 40\%$  and  $\eta_{t\_ref} = 80\%$

**RESEARCH HIGHLIGHTS:**

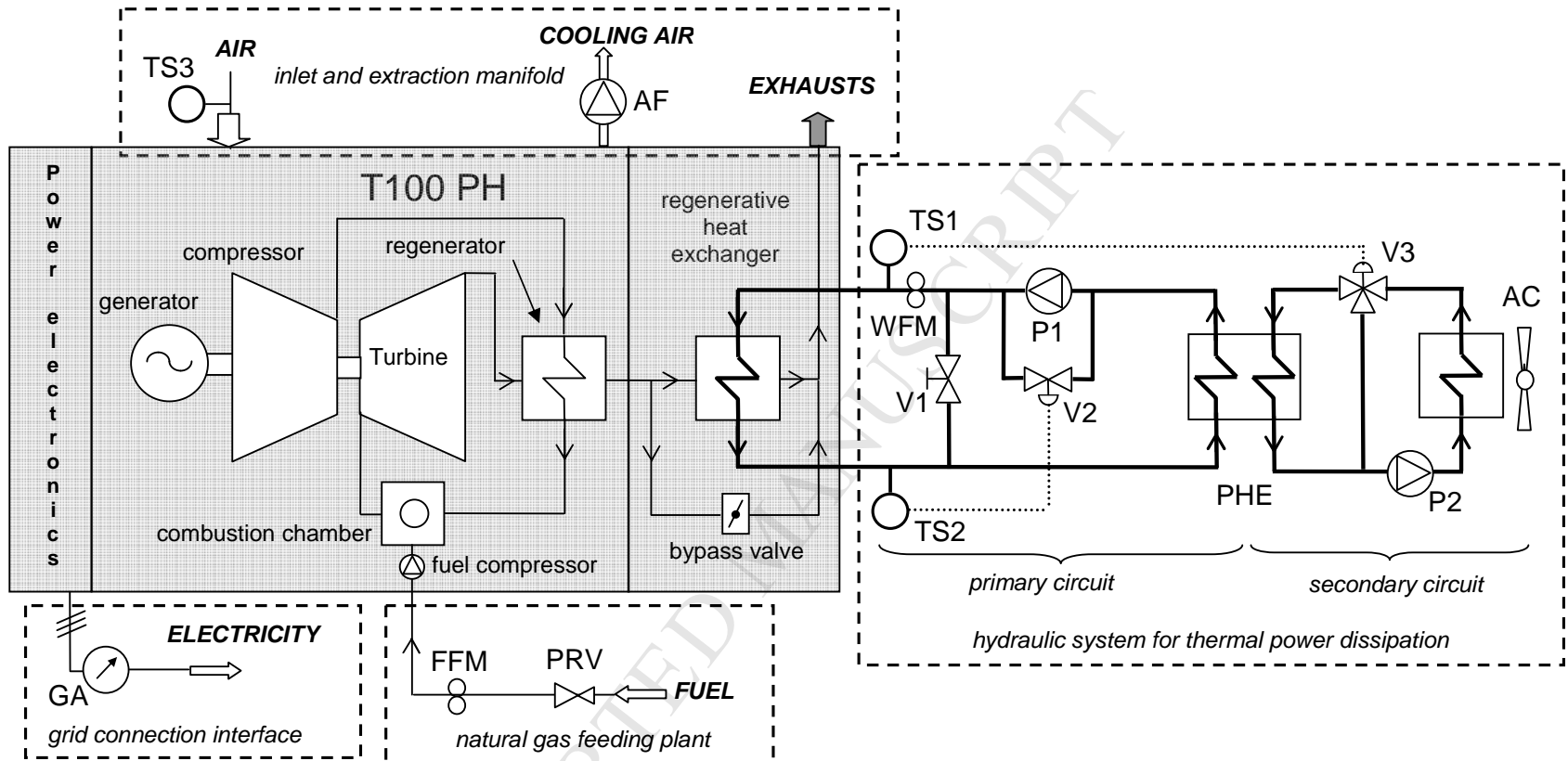
- The test-bed allowed analyzing the MGT in nearly all cogenerative conditions.
- Electrical efficiency reached  $\sim 29\%$  in the 80-100 kW range.
- The maximum thermal power recovered was  $\sim 160$  kW (thermal efficiency  $\sim 44\%$ ).
- Heat priority guaranteed the highest total efficiency ( $\sim 74\%$ ) and *PES* ( $\sim 0.23$ ).
- $\text{NO}_x$  were  $< 6$  ppmv, CO were  $\sim 10$  ppmv at nominal load and increased at low power.

Electrical power	100 kW $\pm$ 3 kW
Thermal power	155 kW $\pm$ 5 kW
Fuel consumption (Natural gas, LHV = 49000 kJ/kg)	24.5 kg/h
Electrical efficiency	30 % $\pm$ 1 %
Thermal efficiency	46.5 % $\pm$ 1.5 %
Total efficiency	76.5 % $\pm$ 2.5 %
Exhaust gas mass flow	0.80 kg/s
Exhaust gas temperature	270 °C
NOx and CO emissions	< 15 ppmv at 15 % O <sub>2</sub>

<sup>a</sup>Data based on ISO standard conditions: ambient pressure 101.3 kPa, ambient temperature 15 °C, ambient relative humidity 60 %, and pressure drops at the inlet and at exhaust 0 Pa



Measured quantity	Measurement equipment	Range	Data sheet technical data
Ambient temperature	Delta Ohm DO9861T	-50 °C... +199.9 °C	Sensor: Pt100 Range: -5 °C÷45 °C Analog output :4÷20mA Accuracy: 0.2°C±0.1% of reading ±0.01 °C/°C
Natural gas mass flow rate	Micro Motion® ELITE® Coriolis Flow Meter CMF025	Max flow rate 2180 kg/h	Accuracy ±0.35% of rate Repeatability ±0.20% of rate
Electrical power	Grid Analyzer EMA 14	-	Accuracy: < 1 %
NO <sub>x</sub> concentration	HORIBA PG-250	0-25 ppm	Repeatability: ±0.5 % of F.S.(NO <sub>x</sub> ≤100 ppm range) Linearity: ±2.0 % of F.S. Drift: ±1.0 % of F.S./day
CO concentration	HORIBA PG-250	0-2000 ppm	Repeatability: ±0.5 % of F.S.( CO ≤1000 ppm) Linearity: ±2.0 % of F.S. Drift: ±1.0 % of F.S./day
RHE water inlet temperature ( $T_{w\ in}$ )	PT100	0-100 °C	Accuracy: ±0.35 °C
RHE water outlet temperature ( $T_{w\ out}$ )	PT100	0-100 °C	Accuracy: ±0.35 °C
Water flow meter	ABB DE43F	0-9 m <sup>3</sup> /h	Sensor: magnetic Accuracy: ±0.5 % of measured value



AC air cooler  
 AF air cooling fan  
 FFM fuel flow meter  
 GA grid analyzer  
 P1 primary circuit pump  
 P2 secondary circuit pump  
 PHE plate heat exchanger  
 PRV fuel pressure reduction valve

TS1 temperature sensor for  $T_{w\_in}$   
 TS2 temperature sensor for  $T_{w\_out}$   
 TS3 air temperature sensor  
 V1 manual needle valve  
 V2 pneumatic valve  
 V3 pneumatic mixing valve  
 WFM water flow meter

