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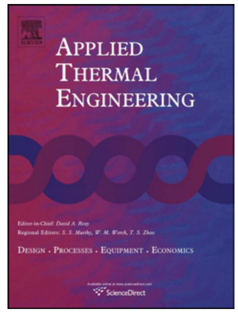

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Use of a test-bed to study the performance of micro gas turbines for cogeneration applications

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Abstract

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

In the tests electrical power ranged between 40 and 100 kW; electrical efficiency reached ~ 29 % in the 80-100 kW range. Analysis of the performance of the recovery heat exchanger at different values of inlet and outlet water temperature and flow rate showed that the maximum thermal power recovered was ~ 160 kW and the maximum *PES* index was about 24 %. With regard to the main pollutants at the exhaust, NO_x concentrations were < 6 ppmv in the whole MGT working range, while CO concentrations increased substantially at low electrical power values, starting from around 10 ppmv at nominal load.

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

1. Introduction

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

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

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

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

Nomenclature

CHP	combined heat and power
c_w	average specific heat of the water inside the RHE (kJ/kg K)
HVAC	heating, ventilation and air conditioning
LHV	natural gas lower heating value (kJ/kg)
$\dot{m}_f$	natural gas mass flow rate (kg/h)
MGT	micro gas turbine
P_e	electrical power (kW)

PES primary energy saving

P_{th} thermal power (kW)

P_{th}^0 thermal power with the bypass valve in fully closed position (kW)

PTH% percent thermal power recovered

Q_w volumetric flow rate of the water in the primary circuit (l/s, l/min)

RHE recovery heat exchanger

T_{w_in} RHE water inlet temperature (°C)

T_{w_out} RHE water outlet temperature (°C)

η_e electrical efficiency

η_{e_ref} separate generation system reference electrical efficiency

η_{th} thermal efficiency

η_{th_ref} separate generation system reference thermal efficiency

η_{tot} total efficiency

ρ_w density of the water in the primary circuit at the RHE inlet (kg/m^3)

2. The cogeneration micro gas turbine

The machine chosen for the tests was a Turbec T100 PH cogeneration MGT based on a regenerative Brayton cycle; it is a more recent version of the one investigated by Colombo et al. [18] and features an embedded fuel compressor. The unit is fired with natural gas and the combustor, a lean-premixed-low-emission type, guarantees volumetric concentrations of NOx and CO < 15 ppmv at 15% O_2 at full load.

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

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

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

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

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

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

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

3. Test-bed

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$P_{th} = \rho_w Q_w c_w \left(T_{w\_out} - T_{w\_in}\right) \quad 1)$$

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

$$\eta_{th} = \frac{P_{th}}{\dot{m}_f \ LHV} \tag{3}$$

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

4.1. Cogenerator performance at nominal inlet thermal conditions

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

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

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

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

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

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

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

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

The total efficiency data are reported in the performance chart next to each experimental point; the corresponding outlet temperature, T_{w_out}, can be read on the secondary axis on the right.
The total efficiency data are also reported in figure 3 with the electrical efficiency data. For each working point, thermal efficiency is the difference between total and electrical efficiency.
The average electrical efficiency is 28.5 % at maximum load, peaking at about 29.5 % for a net electrical power of 80 kW. Furthermore, efficiency declines to an average of 23.5 % at 40 kW. Taking into account inlet and exhaust duct pressure losses, these values are consistent with those stated in the manufacturer’s data sheet [17].
Figure 3 shows that the electrical efficiency does not depend on the position of the bypass valve (i.e. on operating mode); rather, for each electrical power setting the lower the thermal power demand (i.e. the greater the bypass valve opening), the lower the thermal efficiency (and thus total efficiency). For example, at 100 kW of electrical power, total efficiency is 74 % with the valve fully closed (thermal priority) and 36 % with the valve fully open (see also the data in figure 2).
At the same time, for a given level of thermal power demand the greater the electrical power produced, the lower total efficiency. For example, it can be seen from figure 2 that the unit produces about 80 kW of thermal power either working in thermal priority mode, at 40 kW of electrical power, or working in electrical priority mode, at 100 kW of electrical power with the bypass valve about 1/3 open. In the former case total efficiency is around 74 %, in the latter it is slightly more than 51 %.
Finally the concentrations of the primary pollutants [21] at 15 % O_2 dilution are reported in the performance chart. NO_x were low in the whole electrical working range of the MGT, with a peak of ~6 ppmv in correspondence with the machine’s minimum load; CO concentrations < 10 ppmv were measured at 100 and 80 kW, while at lower electrical power settings concentrations were significantly higher, with a maximum of 1550 ppmv at 40 kW.

4.2. Cogenerator performance at nominal electrical power

In this section the data show how water parameters at the RHE influence the recoverable thermal power when the system is working with the bypass valve fully closed (i.e. in thermal priority mode).
For each electrical power setting, the recoverable thermal power depends on the water parameters, because whereas modification of inlet water parameters does not change the temperature and amount of the exhausts

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

Here we focus on the 100 kW nominal electrical power point; the next section addresses lower power values. Two experimental data sets are compared in figure 4, one regarding the RHE fed with the nominal mass flow rate of water at different temperatures and the other regarding the RHE fed with different mass flow rates at the nominal inlet temperature. The parameters (thermal power recovered, mass flow rate and inlet temperature) are reported as a function of outlet temperature.

As shown by the tendency lines, the data sets of the two cases (represented respectively as circles and squares in 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.

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

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

4.3. Cogenerator performance at nominal water inlet and outlet temperatures

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

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

The data of the two cases converge at the nominal values. Starting from the nominal point, if the electrical power is reduced while keeping the inlet and outlet temperature at 50 °C and 70 °C, respectively (squares in figure 5), less thermal power is recovered with respect to the other case (circles). Alternatively, if the electrical power is reduced while keeping the mass flow rate constant at 2 l/s and the inlet temperature at 50 °C (circles), the temperature at the RHE outlet decreases; the mean temperature difference between the MGT exhausts and water is greater than in the previous case, and more thermal power is recovered accordingly.

5. Primary energy saving

To complete the analysis of the cogeneration unit this section reports some data relating to the comparison with a conventional separate generation system, which are useful to evaluate the practical use of the cogeneration unit. From the energy point of view, this is done through the *PES* index, which quantifies the amount of primary energy that can be saved by heat and power cogeneration compared with separate generation, as:

$$PES = 1 - \frac{1}{\frac{\eta_e}{\eta_{e\_ref}} + \frac{\eta_{th}}{\eta_{th\_ref}}} \qquad 6)$$

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

6. Conclusions

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

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

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

Analysis of different electrical power settings between 40 and 100 kW yielded a maximum electrical efficiency of ~ 29.5% at 80 kW and a minimum of ~ 23.5% at 40 kW.

As regards pollutants, NO_X concentrations were very low in all working conditions, while CO concentrations were low at high-medium power and rose steeply at lower loads.

The tests showed heat priority operation to be the most efficient mode, as reflected both in total efficiency and in *PES* index values, and cogeneration with electrical priority to be the least efficient mode, due to bypass valve opening, hence to the amount of heat discharged. A negative *PES* was actually found in a number of conditions with the bypass valve not closed, demonstrating that the electrical priority mode may be less efficient than separate production. The maximum thermal power recovered was about 160 kW, with a thermal and a total efficiency around 44 % and 74 %, respectively.

When the cogenerator was compared with standard separate production with η_{e_ref}= 40 % and η_{th_ref} = 80 % the maximum *PES* index was about 0.23.

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Table captions

Table 1. Micro gas turbine performance in nominal conditions[a]

Table 2. Measurement instruments

Figure captions

Figure 1. Layout of the MGT cogeneration test-bed

Figure 2. MGT performance chart in nominal inlet thermal conditions

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

Figure 4. MGT thermal performance at nominal electrical power

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

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

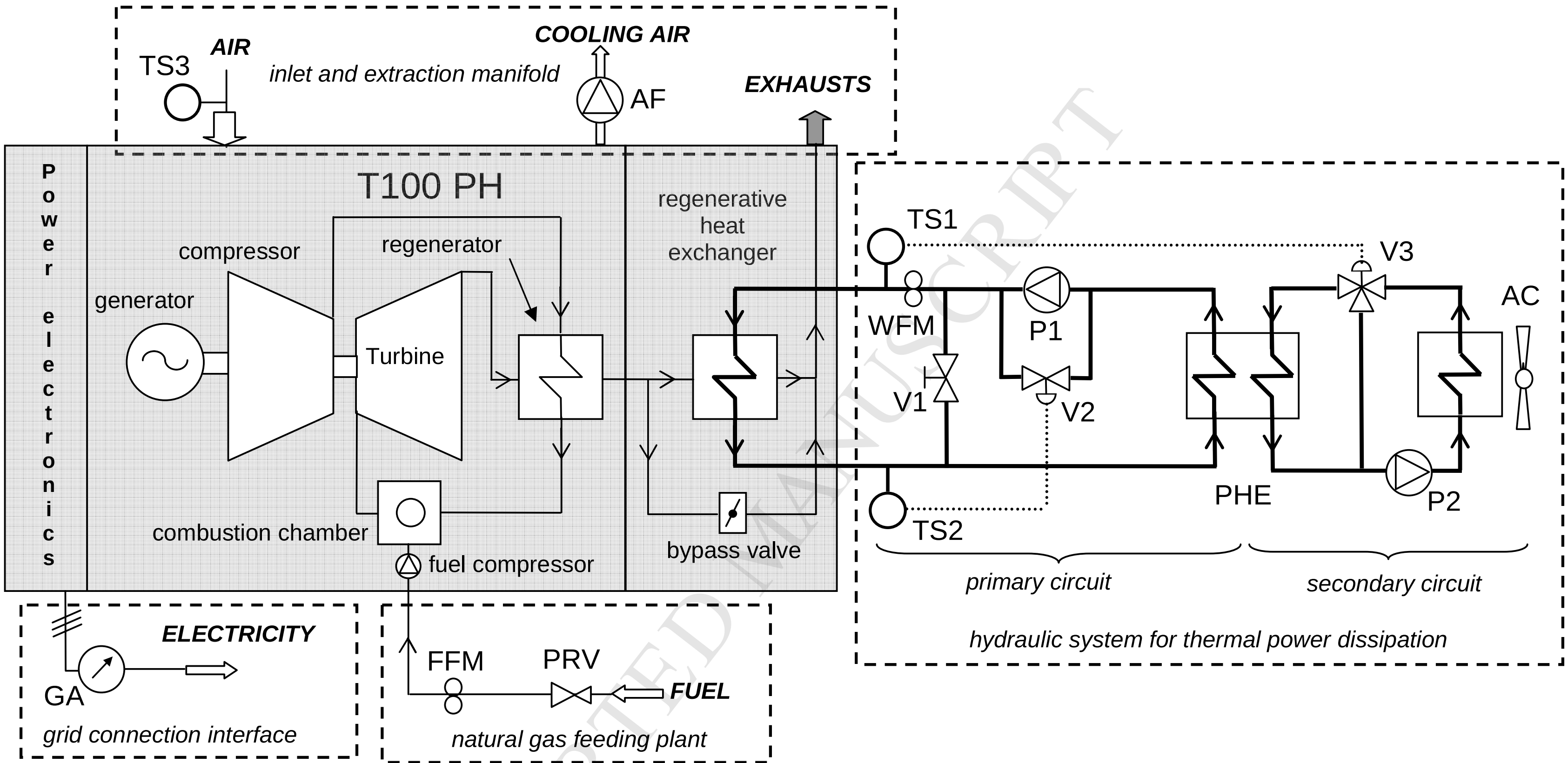
RESEARCH HIGHLIGHTS:

- The test-bed allowed analyzing the MGT in nearly all cogenerative conditions.
- Electrical efficiency reached ~ 29 % in the 80-100 kW range.
- The maximum thermal power recovered was ~160 kW (thermal efficiency ~44 %).
- Heat priority guaranteed the highest total efficiency (~74 %) and *PES* (~ 0.23).
- NO_x were < 6 ppmv, CO were ~10 ppmv at nominal load and increased at low power.

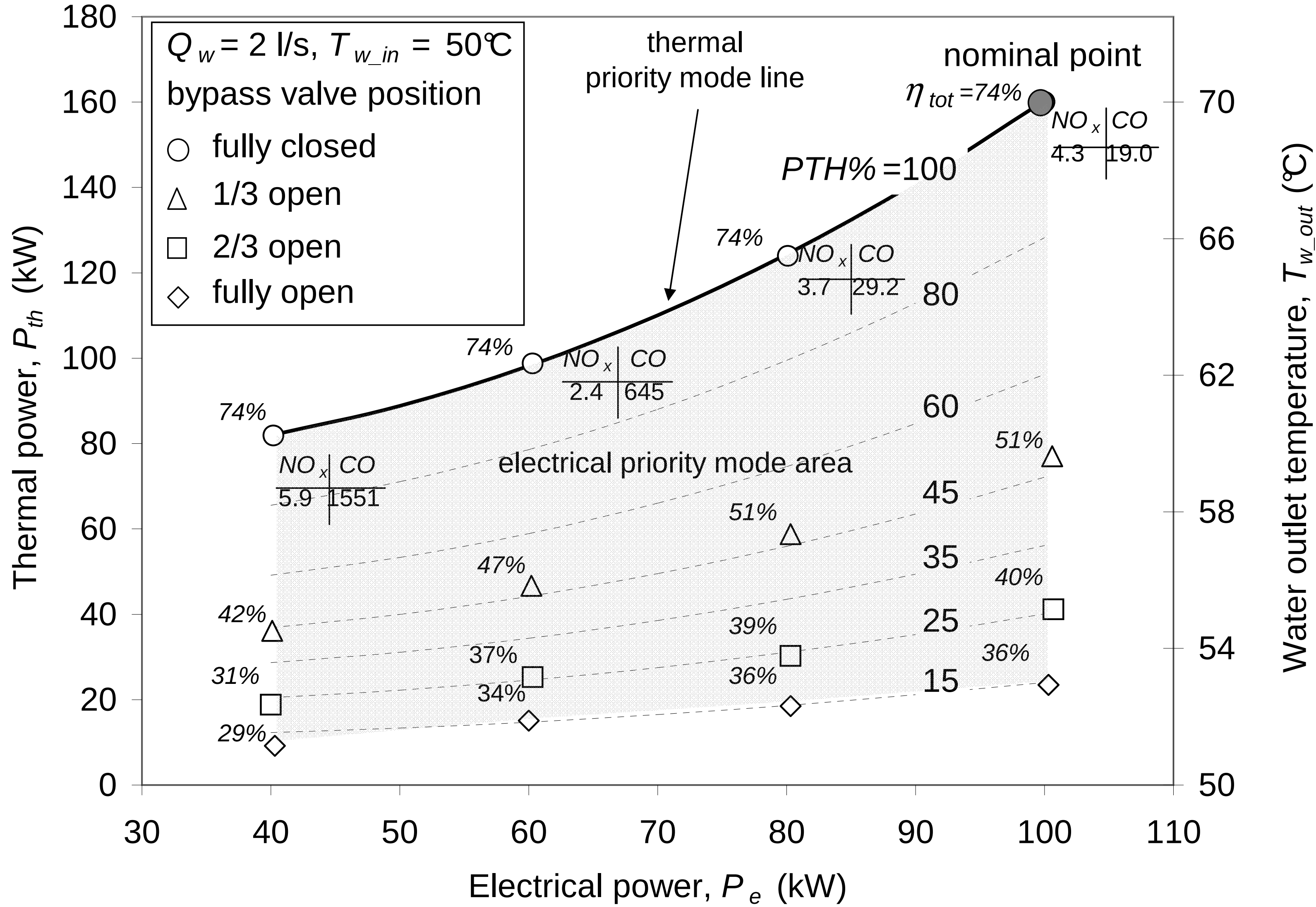
Electrical power	100 kW ± 3 kW
Thermal power	155 kW ± 5 kW
Fuel consumption (Natural gas, LHV = 49000 kJ/kg)	24.5 kg/h
Electrical efficiency	30 % ± 1 %
Thermal efficiency	46.5 % ± 1.5 %
Total efficiency	76.5 % ± 2.5 %
Exhaust gas mass flow	0.80 kg/s
Exhaust gas temperature	270 °C
NOx and CO emissions	< 15 ppmv at 15 % O_2

[a]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

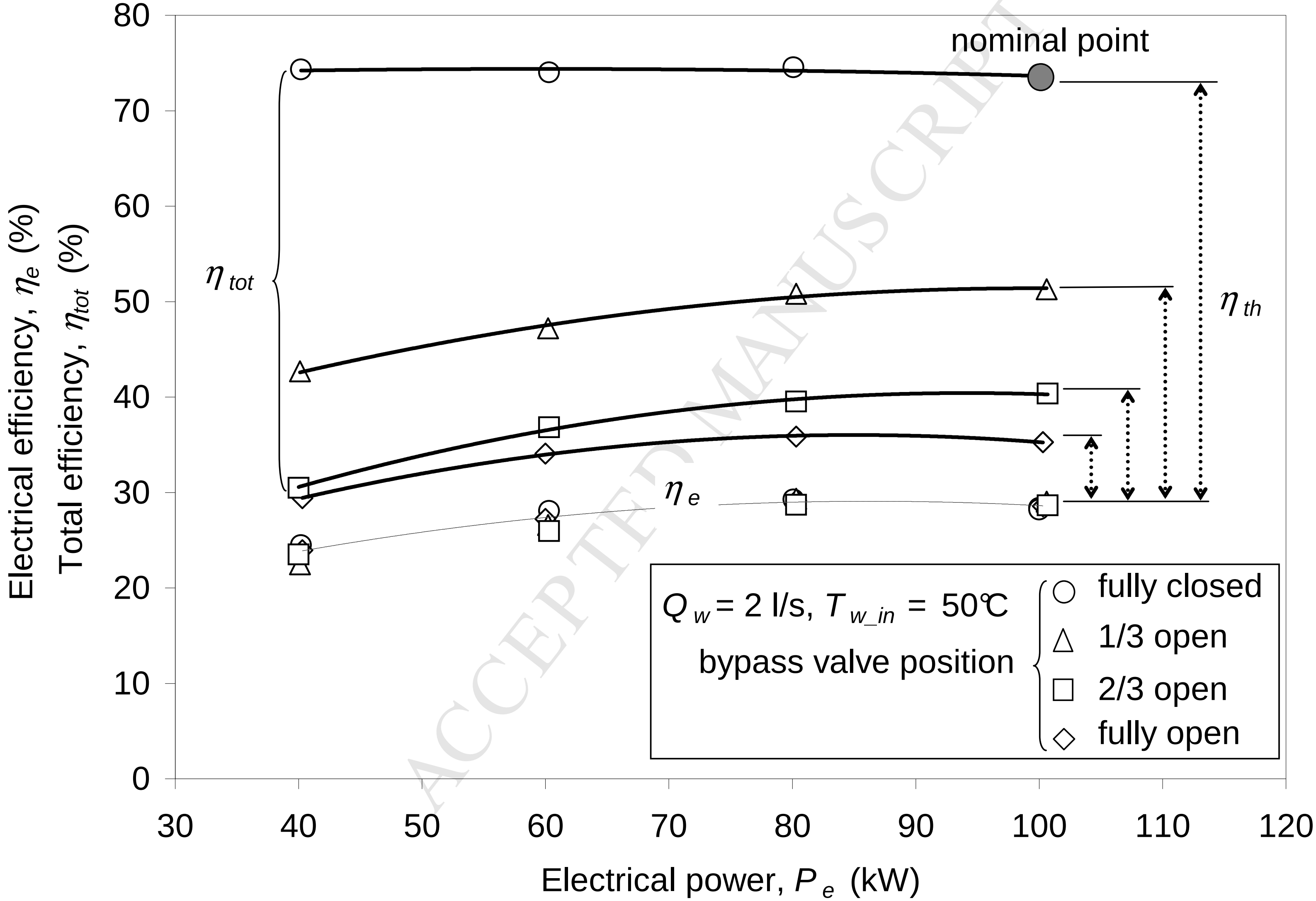
Measured quantity	Measurement equipment	Range	Data sheet technical data
Ambient temperature	Delta Ohm DO9861T	-50 °C… +199.9 °C	Sensor: Pt100 Range: -5 °C÷45 °C Analog output :4÷20mA Accuracy: 0.2°C±0.1% of reading ±0.01 °C/°C
Natural gas mass flow rate	Micro Motion® ELITE® Coriolis Flow Meter CMF025	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_x concentration	HORIBA PG-250	0-25 ppm	Repeatability: ±0.5 % of F.S.(NOx ≤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^3/h	Sensor: magnetic Accuracy: ±0.5 % of measured value



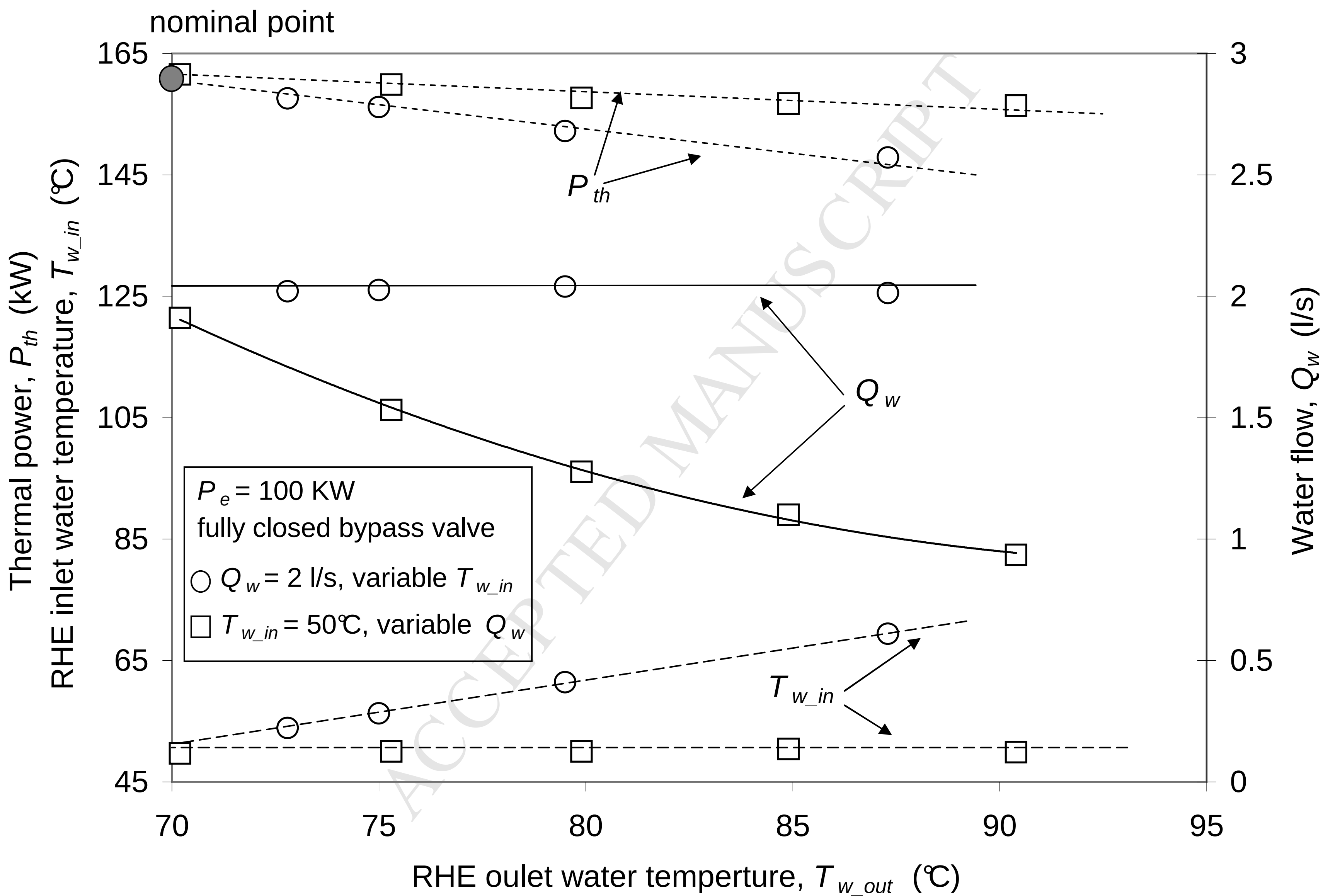
AC	air cooler	TS1	temperature sensor for T_{w_in}
AF	air cooling fan	TS2	temperature sensor for T_{w_out}
FFM	fuel flow meter	TS3	air temperature sensor
GA	grid analyzer	V1	manual needle valve
P1	primary circuit pump	V2	pneumatic valve
P2	secondary circuit pump	V3	pneumatic mixing valve
PHE	plate heat exchanger	WFM	water flow meter
PRV	fuel pressure reduction valve		

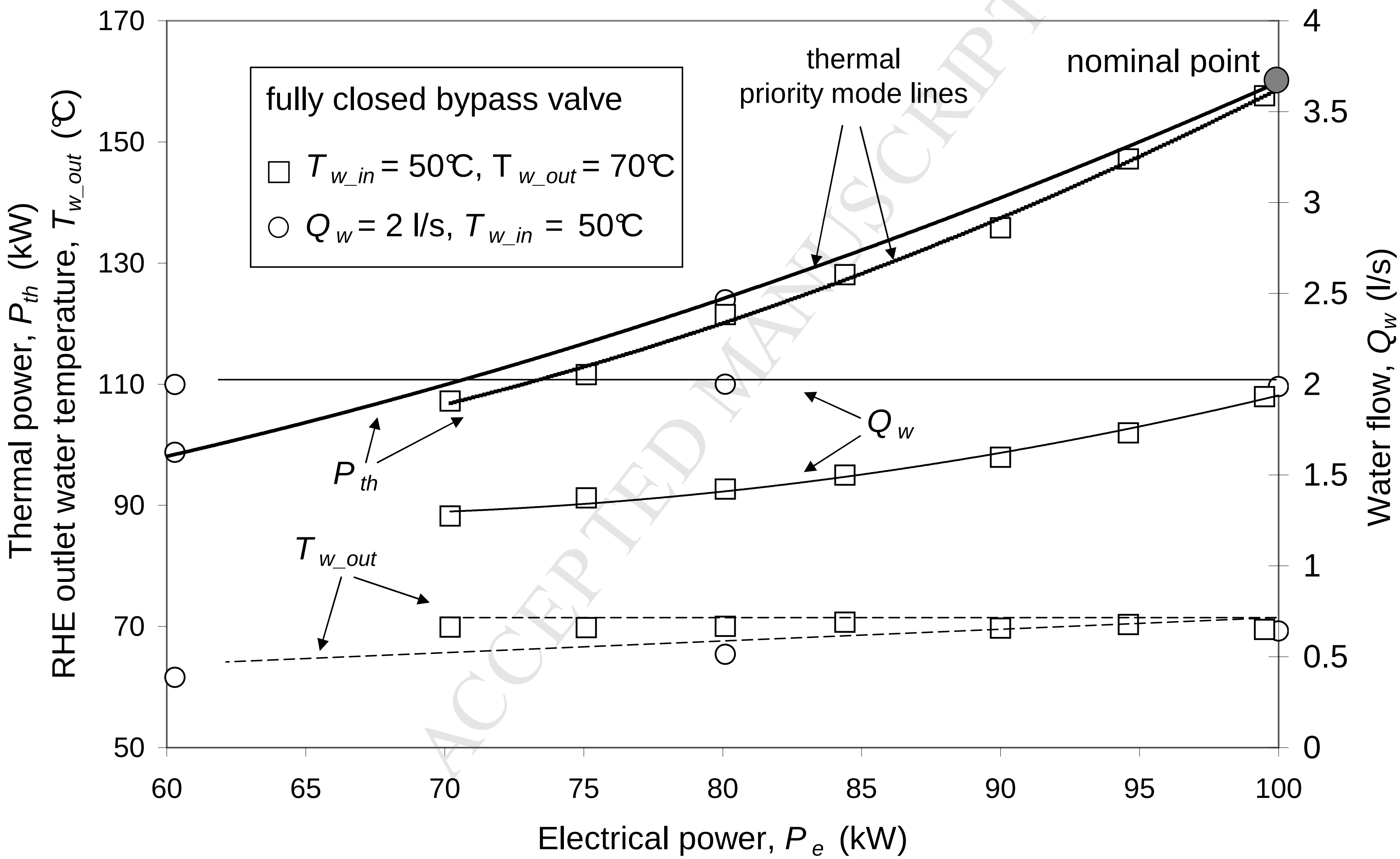


Q w = 2 l/s, T w_in = 50℃
bypass valve position
fully closed
1/3 open
2/3 open
fully open
thermal priority mode line
nominal point
η tot =74%
PTH% =100
80
60
45
35
25
15
electrical priority mode area
NO x CO 4.3 19.0
NO x CO 3.7 29.2
NO x CO 2.4 645
NO x CO 5.9 1551
74%
51%
47%
42%
40%
39%
37%
36%
34%
31%
29%
Thermal power, P th (kW)
Electrical power, P e (kW)
Water outlet temperature, T w_out (℃)
0
20
40
60
80
100
120
140
160
180
30
40
50
60
70
80
90
100
110
50
54
58
62
66
70

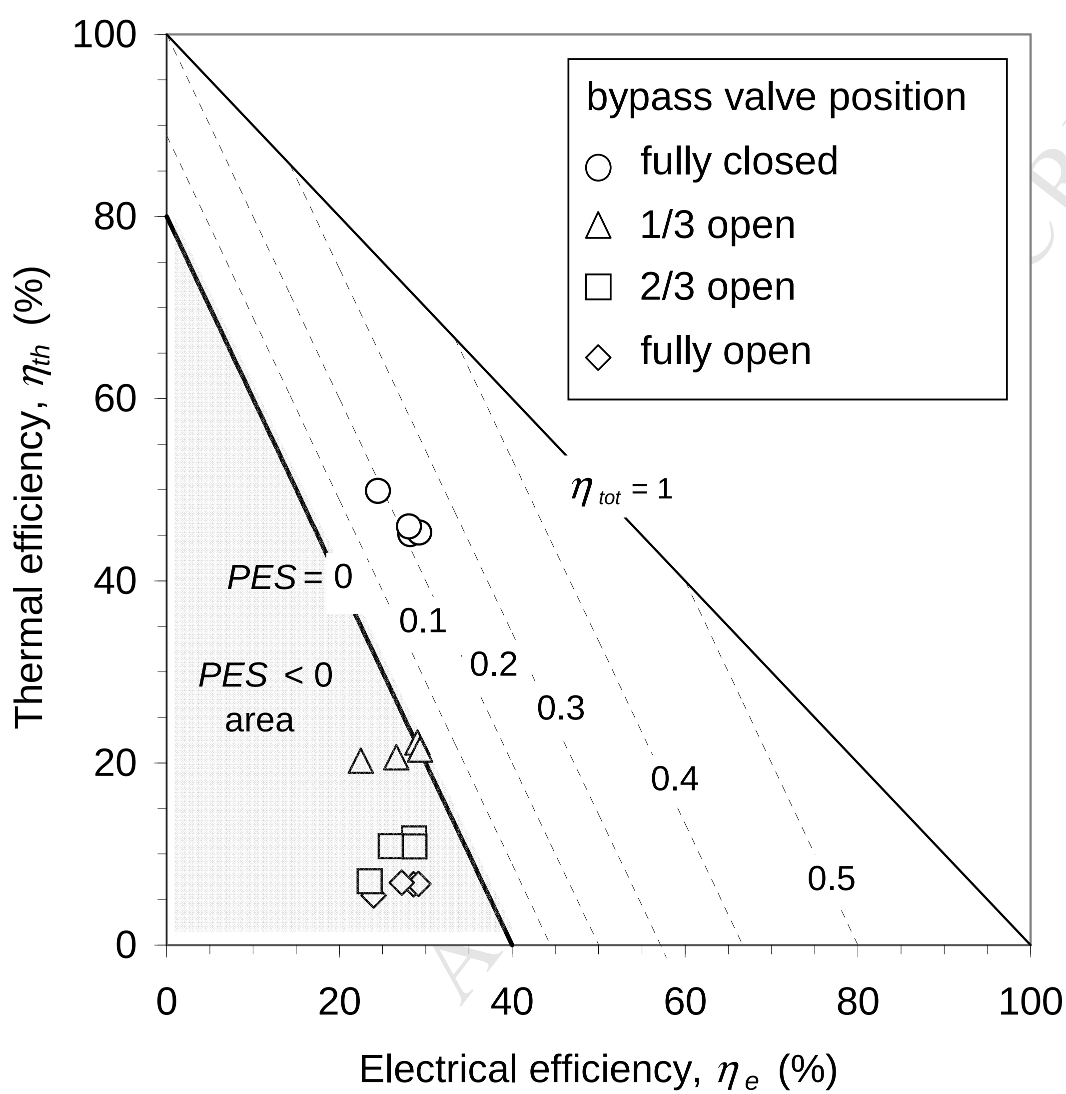


80
70
60
50
40
30
20
10
0
30
40
50
60
70
80
90
100
110
120
Electrical power, P_e (kW)
Electrical efficiency, η_e (%)
Total efficiency, η_{tot} (%)
nominal point
η_{tot}
η_{th}
η_e
Q_w = 2 l/s, T_{w_in} = 50℃
bypass valve position
fully closed
1/3 open
2/3 open
fully open


nominal point
165
145
125
105
85
65
45
3
2.5
2
1.5
1
0.5
0
70
75
80
85
90
95
P th
Q w
T w_in
P e = 100 KW
fully closed bypass valve
Q w = 2 l/s, variable T w_in
T w_in = 50℃, variable Q w
Thermal power, P th (kW)
RHE inlet water temperature, T w_in (℃)
Water flow, Q w (l/s)
RHE oulet water temperture, T w_out (℃)
ACCEPTED MANUSCRIPT



170
150
130
110
90
70
50
4
3.5
3
2.5
2
1.5
1
0.5
0
60
65
70
75
80
85
90
95
100
Thermal power, P th (kW)
RHE outlet water temperature, T w_out (℃)
Water flow, Q w (l/s)
Electrical power, P e (kW)
fully closed bypass valve
T w_in = 50℃, T w_out = 70℃
Q w = 2 l/s, T w_in = 50℃
thermal
priority mode lines
nominal point
Q w
P th
T w_out


bypass valve position
fully closed
1/3 open
2/3 open
fully open
η tot = 1
PES = 0
PES < 0
area
0.1
0.2
0.3
0.4
0.5
Thermal efficiency, ηth (%)
Electrical efficiency, ηe (%)
0
20
40
60
80
100