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Performance analysis of a solar-only gas micro turbine, with mass flow control.

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Abstract

Micro gas turbine applications in concentrating solar field systems is already on industrial stage. The peculiarity of these systems is the possibility to use fossil fuels when solar power source is lacking .It is preferable that the system works in solar-only mode for long time; however, owing to the efficiency loss which occur for low radiation levels, a fuel integration is necessary.

This work presents a system which allows to operate with constant efficiency, without the use of fuel for over one fifth of the nominal power rate. It is based on a regenerated micro gas turbine in closed loop configuration. The proposed system includes the solar tower, the heliostats field, the regenerator and a low temperature heat exchanger which cools the working fluid. Finally, two more devices, for the actuation of the proposed control are included: an auxiliary compressor and a bleed valve.

The use of air as working fluid has been analyzed, with different values of the base cycle pressure (inlet pressure of the main compressor), which are needed for varying the mass flow flowing in the system. The control of the mass flow rate is mandatory to regulate the gas turbine power, by keeping almost constant the maximum temperature of the thermodynamic cycle when the incident solar radiation changes. In particular, the auxiliary compressor admits fresh air in the cycle when the thermal power received by the sun increases, while the bleed valve discharges it in the atmosphere, when the thermal power decreases. Therefore, the thermodynamic cycle is unchanged and guarantees constant net system efficiency for all the operations conditions.

Particular attention is given to the receiver thermal incident flux, heliostat field and solar tower design. The current results are compared with the annual efficiency and energy production of an existing plant in hybrid configuration (solar-fuel).The analysis has been carried out on a commercial gas turbine having a power of 100 kW, sited on Seville town. For the heliostat field analysis, the open source code Solar PILOT has been used, while for the entire plant the code Thermoflex has been employed.

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Keywords: Micro gas turbine, solar tower,concentrating solar power, air cloosed loop Brayton cycle

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1. Introduction

Gas turbines driven by concentrating solar system concept is not recent, but some study and experimental test was performed formerly during first years of ’80 of last century. Scheuerer [1] and Schmuttermair [2] used a modified Allison 250-C20B helicopter engine for their test; their research activity laid the groundwork for pressurized air receiver design, as well as dynamic simulation and control of solar gas- turbines.

During 2000s EU-funded projects have supported and examined some small-scale hybrid solar gas-turbines such as Solgate [3] and Solhyco [4] projects.

These projects have demonstrated the possibility of using a solarized micro gas turbine unit up to 250 kW, and for this reason different height temperature pressurized solar air receivers, with outlet air temperature up to 900 °C, were developed.

The FP6 Solhyco project also demonstrated the potential of using sustainably derived biodiesel as a hybridization fuel.

The FP7 EU funded Solugas project allowed the construction of a solar hybrid gas turbine system of about 5 MWe based on a SolarMercury 50 [5].

Some studies about the possibility of solar gas-turbine were performed by a research group financed from Google too, for 1 MW engine power rating.

Currently, the only gas turbine solar hybrid system available on the market is produced by Aora-Solar [6] providing a unit 100 kW for off grid and cogeneration applications and installed successfully as test in Spain and Israel.

Nowadays the attention, in CRS (central receiver systems), is posed on the use of solar-only driving to achieve high cycle efficiency and zero emission. Examples are the systems based on SCO2 solar gas-turbine [7] and, recently, the use of air as HTF [17] or Synthetic oil [19] coupled with storage.

Energy policies are promoting implementation of renewable energy systems focusing on the sources such as wind or solar, by providing management tools such as Sustainable Energy Action Plans [8].

Yet, the associated scenario with high share of renewable energy generation requires a deep understanding of the interaction between the new green production and the existing fossil-based one.

Recent studies demonstrated how the transition could be handled starting from introducing a renewable fraction in the well-established technologies already installed in the buildings such as boilers [9] or Combined Heat and Power [10].

Indeed, different technologies from prime mover to heat producer could be coupled with renewable-based systems. This is the pathway for systems’ hybridization. Furthermore, another viable option is the partial or total substitution of the fuel for feeding the machines by the use of synthetic ones coming from biomass treatment, fossil fuel reforming, water electrolysis or gas hydrates [11].

This strategy could be successfully driven if local policy instruments are available along with energy analysis such as for urban contexts [12].

In this paper, the coupling between a micro-gas turbine driven by only solar tower and receiver system is presented; above all, the authors examined the possibility of using air as a working fluid.

Plant description

Figure 1 shows the plant of the proposed system. It is possible to note the main compressor (1), the solar tower (2), the turbine (3), the heliostat field (4), the recuperator (5), the low temperature heat exchanger (6), the auxiliary compressor (7), the bleed valve (8), and the evaporative tower (9).

The air mass flowing in the plant loop varies depending on DNI and sun position. When the irradiance rises, the auxiliary compressor sends air to the suction side of the main compressor (or micro gas-turbine inlet); vice versa, when sun power decreases, the bleed valve discharges air towards the atmosphere.

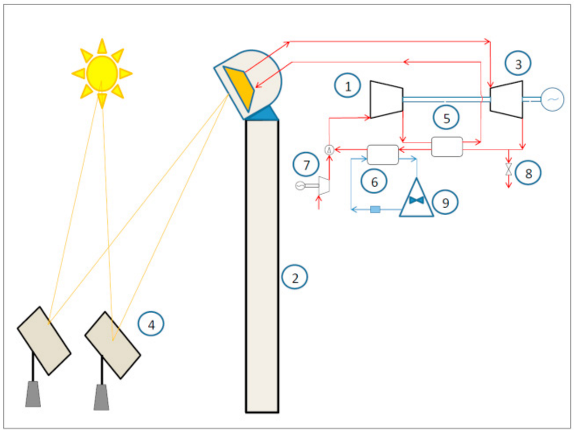

Fig. 1. Entire plant: (1) main compressor, (2) solar tower, (3) turbine, (4) heliostat field, (5) recuperator, (6) low temperature heat exchange,(7) auxiliary compressor, (8) bleed valve, (9) evaporative tower .

The heat exchanger is used to cool the air mass flow exit from the turbine at the initial condition. This way the characteristic temperatures (TIT, TOT, inlet and outlet compressor) of the cycle don't change when the system performs (for different load or DNI).

So the closed loop cycle makes it possible to control power, keeping constant the cycle efficiency during DNI variation.

Nomenclature

TIT	Temperature Inlet Turbine (°C)
TOT	Temperature Outlet Turbine (°C)
DNI	Direct Normal Irradiance (W/m^2)
SM	Solar Multiple
µGT	Micro gas-turbine
P	Mean pressure of the cycle (bar)
V	Internal volume of the entire plant (compressor, receiver, turbine, heat exchanger) (m3)
n	Mole number
R	Universal gas constant 8314 J/(mol K)
Q	Turbine outlet power (kW)
C_p	Average specific heat of the air J/(kg K)
$\dot{m}$	Mass flow flowing in the cycle (kg/sec)
$T_{o,com}$	Outlet temperature of the compressor (°C)
CDF	Cumulative distribution function
TMY	Typical meteorological year
PSA	Plataforma Solar de Almeria
HTF	Heat transfer fluid
ΔE	Energy variation (MWh)
N_H	Heliostats number
$E_{SM(i+1)}$	Energy product for solar multiple next configuration (MWh)
$E_{SM(i)}$	Energy product for solar multiple precedent configuration (MWh)
$N_{hSM(i+1)}$	Heliostats number for solar multiple next configuration
P_{th}	Net receiver thermal power transfer to the fluid (kW)
Pel	Electric nominal power of µGT
η_c	µGT nominal efficiency

2. Methodology

In this work the performance of a micro gas-turbine working in solar-only mode has been analyzed. So, the optimization of the heliostat field and the receiver plays an important role. An efficient solar field lets the system work for many hours, increasing the energy production.

For this reason, particular attention to the optimization of these system parts has been devoted. Different configurations (in terms of SM) have been explored using the open source software SolarPILOT based on DelSol3code.

To simulate the entire plant in Thermoflex software, the performance map of Ansaldo Energia-Turbec T100 micro gas-turbine's [13] compressor and turbine has been implemented. To characterize the solar field in Thermoflex, the Solar PILOT results (in terms of flux map, heliostat number, receiver dimension) have been utilized. The Thermoflex results have been compared in terms of energy production, net electric efficiency, and operation hours, with ones of the commercial system Aora Tulip [14] (based on Turbec T100 micro gas-turbine).

2.1. Micro gas-turbine configuration

The gas-turbine implemented in the software is the 100 kW Turbec T100 micro gas-turbine. The performance map of both compressor and turbine have been implemented in Thermoflex, to perform off-design mode simulation. Figure 2a and 2b show these two maps.

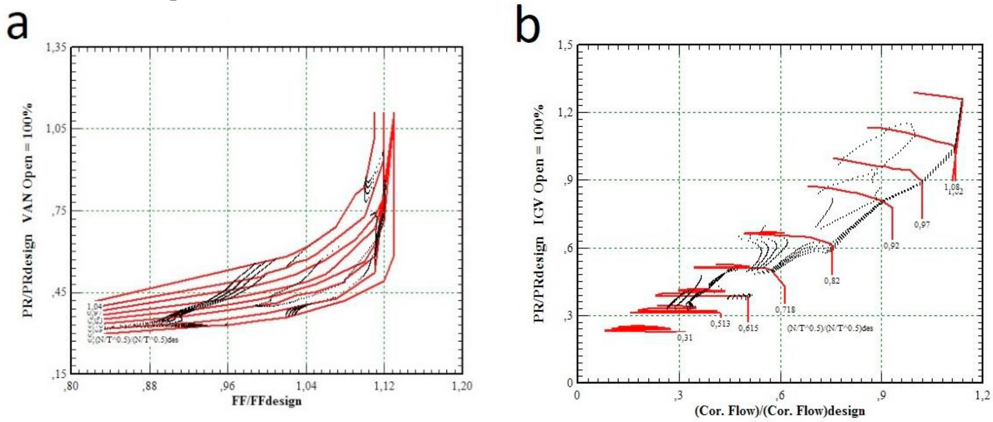

Fig. 2. (a) Turbine map; (b) Compressor map.

It is worth pointing out that in the proposed system, the input pressure of μGT is increased (by the auxiliary compressor) about 5 times the nominal one (the atmospheric pressure). We chose this value because the use of a pressurized volumetric receiver was supposed; so, considering that the compressor ratio is 4.5 [13], the maximum receiver pressure doesn't surpass 25 bars without damaging materials.

On the other hand, by increasing the cycle pressure base, the mass flow rate circulating in the plant rises. If we considering the ideal gas law:

$$PV = nRT \quad (1)$$

Increasing the pressure causes the mole number to rise up, because we fixed the cycle maximum temperature (e.g. receiver's exit air temperature) and the plant internal volume.

As described above, the main cycle temperature does not change nor the volumetric flow is altered. The density, because of the pressure effect, changes its value and then the mass flow rate.

Since the turbine's power is described by equation 2:

$$Q = \dot{m}\, Cp\, (TIT - T_{o,com}) \quad (2)$$

by increasing the pressure base 5 times, the mass flow increases directly of the same magnitude, as well as the turbine power. In this case, the power peak moves from 100 kW to 500 kW.

2.2. Solar field and receiver configurations

As described in the previous section, the nominal power of the micro gas-turbine gets to 500 kW in closed loop configuration, so this is the reference power parameter for designing the solar field.

First of all, the same efficiency of the 100 kW μGT has been considered, as well as the polytrophic efficiency, compressor ratio and rpm.

We designed the solar field and the receiver for different SM from 1 to 1.5. We considered an average flux incident on the receiver of 400 kW/m2 [15], an absorbance of 94 %, and a reflectivity of 92% for the heliostats. To choose the DNI design point, we use the 95th percentile of the CDF from data of TMY of Seville [16], which is 850 W/m2. The thermal peak power required for the cycle was estimated as:

$$P_{th} = P_{el}/\eta_c \quad (3)$$

For each configuration we estimated, by iterative calculation, the receiver area, tilt receiver angle, tower height, the heliostat area, and finally optical efficiency matrix. The solar field's best configuration was then implemented to initialize the next power block simulation, performed by Thermoflex. The software calculates, in function of Azimuth, Zenith and DNI, the pressure base and the mass flow to keep constant the air exit temperature from the receiver at 800 °C.

It must be noted that the receiver air exit temperature was considered as TIT in this work, because no thermal losses have been taken into account.

3. Results

In this section, we show results of the solar field performed by Solar PILOT and those calculated by Thermoflex, for an entire year for each SM configuration.

These results will be compared with the Aora Tulip installed in PSA (Almeria) [6] in terms of energy production and solar field dimensions.

3.1 Solar field and receiver results

Table 1 shows the solar field and receiver dimensions, while table 2 summarizes the heliostat field's optical property. Figure 3 shows the trend of the thermal power absorbed by HTF, the one absorbed by the receiver and the one incident on the solar field.

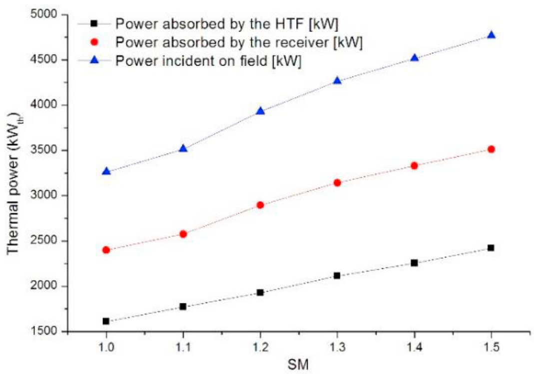

Fig 3. Trend of thermal power absorbed by the HTF, power absorbed by the receiver and incident on the heliostat field, versus solar multipleTable 1. Dimensional data results of solar fields.

SM	Units	1	1.1	1.2	1.3	1.4	1.5
Receiver height	m	2.3	2.4	2.5	2.8	2.8	2.8
Receiver width	m	2.7	2.8	3.1	3	3.2	3.4
Receiver area	m^2	6.21	6.72	7.75	8.4	8.96	9.52
Receiver orientation elevation	deg	-54	-54	-53	-57	-45	-49
Tower height	M	59	59	72	76	79	79
Simulated heliostat count	-	78	84	94	102	108	114
Simulated heliostat area	m^2	3836	4131	4622.8	5016.3	5311.3	5606.4

Table 2. Optical property results of heliostats fields.

SM	Units	1	1.1	1.2	1.3	1.4	1.5
Solar field optical efficiency	%	73.6	73.3	73.7	73.7	73.8	73.7
Cosine efficiency	%	92.9	92.7	93.1	93.1	93.1	93
Attenuation efficiency	%	98.3	98.3	98.1	98.1	98	98
Blocking efficiency	%	99.7	99.7	99.8	99.8	99.8	99.8
Shading efficiency	%	100	100	100	100	100	100
Reflection efficiency	%	87.4	87.4	87.4	87.4	87.4	87.4

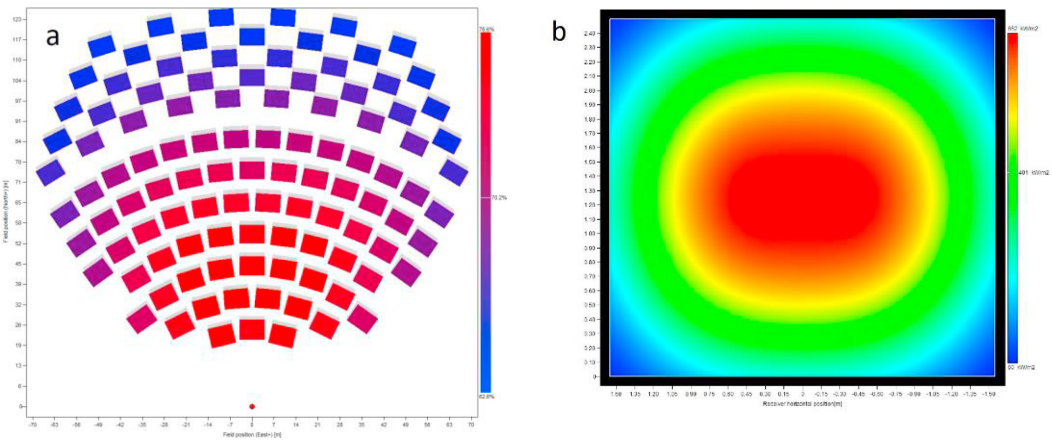

Fig. 4. 1.2 Solar Multiple configuration (a) Heliostat field; (b) Flux incident on the receiver surface

Figure 4 shows the heliostat field (a) and flux map (b) of the receiver for the solar field with SM equal 1.2, as calculated by SolarPILOT.

3.1. Micro gas-turbine and solar field results

Thermoflex simulation results are summarized in table 3; it is possible to notice the hourly energy annual production and the average annual efficiency for each solar field configuration.

Table 3. Entire plant results performed by Thermoflex

SM	Units	1	1.1	1.2	1.3	1.4	1.5
Annual Energy production	MWh	1.19	1.23	1.28	1.31	1.33	1.34
Average annual efficiency	%	29.0	29.3	29.4	29.5	29.5	29.5

The results show how the employment of the closed loop cycle makes it possible to keep the cycle efficiency constant during all operating condition (DNI, hour, day) around the nominal one. It is also possible to observe that in each solar field configuration the annual average efficiency is about the same and near the peak one.

The energy production, as known, increases with SM; to choose the useful solar field configuration, the relation between the energy variation and the heliostat number has been calculated, as described in equation 4.

$$\frac{\Delta E}{N_h} = \frac{E_{SM(i+1)} - E_{SM(i)}}{N_{hSM(i+1)}} \qquad (4)$$

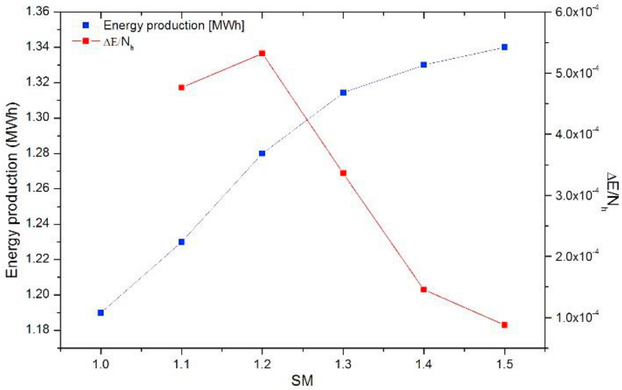

Fig. 5. Relation between energy variation and heliostat number (red line) and energy production (blue line)

In figure 5 it is possible to observe the annual energy trend in blue line and relation ΔE/Nh in red line; the energy trend is increased proportionally with SM, but the relation ΔE/Nh reaches its maximum for values of SM equal to 1.2. Some studies about of the SM choice with the mass flow control system have shown that this value could be acceptable from an economic point of view too [18] .Technically this value could be the best solar field for the closed loop μGT, therefore we compared this configuration with Aora Tulip.

4. Discussion

The Aora Tulip is installed in PSA (Almeria) and in Samara desert (Israel) [6]. We compared performance of the closed system μGT, with SM 1.2 solar field, with the one at PSA.

In table 4 Tulip data [14] are reported; we would like to point out that we compared a hybrid open cycle having a peak power of 100 kW, with an unfired closed cycle of 500 kW peak power (how it became in the new configuration) that uses only air.

Table 4. Aora Tulip data compared with closed loop cycle (SM 1.2)

	Units	AORA Tulip	Closed loop
Receiver height	m	1	2.4
Receiver width	m	1.1	2.8
Receiver area	m 2	1.1	6.72
Tower heigth	m	32	59
Mass flow rate	kg/sec.	0.8	4.8
Outlet receiver temperature	° C	900-1000	800
Heliostat number	-	52	106
Nominal Thermal Power	kW	330	1666.6
Nominal Pressure	bar	4.5	22.5
Annual energy production	MWh	0.78	1.28

In table 4 we can observe that dimensions of the mass flow control system are about 5 times bigger than the one of Aora Tulip. However, the energy production is big too; considering that the starting machine is the same in both cases, the control system adopted in this work could be a convenient choice for small-scale power plants.

5. Conclusions

We analyzed a micro gas-turbine in closed loop configuration driven only by a tower solar system. The parametric analysis on the heliostat field and receiver shows that the compatible solar multiple might be 1.2; in this setup, the energy production is 1.29 MWh and the average electric efficiency is 29%.

This system has been compared to the Aora Solar Tulip; the estimated energy production in PSA was 788,400 kWh [14] with the use of fuel.

Thus, we have estimated that the closed loop micro gas turbine allows to produce (using the same μGT, e.g. Turbec T100) about 38% of energy more than the commercial system Aora Solar Tulip, avoiding fuel usage as well.

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