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HIGH TEMPERATURE STORAGE FOR CSP PLANTS: TEST RIG DYNAMIC ANALYSIS

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ABSTRACT

Hybridized gas turbine cycles are attractive because of their high efficiency, potentially equal to combined cycle efficiency, and dispatchable power capability.

TES technologies are important to accelerate market penetration of CSP plants, overcoming the limitation due to the intermittence of the solar source.

In this work a high temperature ceramic storage Test rig for gas turbine energy systems was presented with its innovative layout, which avoids the use of hot valves. Such experimental plant storage is located at the University of Genoa, Savona Campus, Italy: it can be run with compressed air and it is ready for connection with the modified microturbine T100 onsite. The Test rig represents a scaled-down version of a larger system designed for an hybridized solar 12 MW gas turbine whose dynamics performance was presentedpreviously. This paper presents the dynamic analysis of such lab-scale mGT system, which provided the necessary requirements for the Test rig design.

The storage system proposed here does not involve any hot air valve and does include a short-term (30min equivalent) ceramic thermal storage. The plant dynamic model was developed using the original TRANSEO simulation tool. This paper investigates plant layout control strategy, showing the feasibility of the control procedure through dynamic simulation: eventually, design recommendations are drawn to improve plant flexibility and time response.

NOMENCLATURE

CC	Combustion Chamber or Combined Cycle
CRS	Central Receiver System
CSP	Concentrated Solar Power
Δp	pressure loss
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DoE	Department of Energy
GT	Gas Turbine
η	efficiency
HP	High Power
HRSG	Heat Recovery Steam Generator
LP	Low Power
$\dot{m}$	mass flow
MP	Medium Power
microGT - mGT	Micro Gas Turbine
p	pressure [bar]
P	Power [MW]
PCM	Phase Change Materials
PID	Proportional Integrative Derivative
PLC	Programmable Logic Controller
SGTU	Solar Gas Turbine Upgrade
SHCC	Solar Hybrid Combined Cycle
SSF	Solar Share Factor
T	Temperature [°C]
TES	Thermal Energy Storage
TIT	Turbine Inlet Temperature [°C]
TOT	Turbine Outlet Temperature [°C]
TPG	Thermochemical Power Group

Subscripts

comb	combustor
e	electrical
in	inlet
out	outlet
m	mechanical

1. INTRODUCTION

Among renewable technologies, Concentrated Solar Power (CSP) plants are seen as a viable and competitive option to reduce air pollutants and the emission of greenhouses gases (e.g. CO_2) not only for the United States regions of the Sun Belt (where CSP plants are in commercial use for more than 20 years [1]), but also for European Union, North Africa and Middle East.

CSP technologies are based on the concept of concentrating solar radiation to be used for electricity generation within conventional power cycles using steam turbines, gas turbines or Stirling engines.

Since the sun is an intermittent source of energy, almost every CSP technology can be operated with fossil fuel as well as solar power. This hybrid operation has the potential to increase the value of CSP technology by increasing its power availability and decreasing its cost by enhancing the effective use of the power block.

Concentrating Solar Power (CSP) is achieving a growing penetration into global electricity markets. It has long been recognized that the possibility for the integration of Thermal Energy Storage (TES) is one of the key advantages of CSP over other forms of renewable energy.

TES integration allows excess solar energy to be harnessed during the daytime and stored, as thermal energy, to be used during times of insufficient solar supply, such as in cloudy hours or at night. In this way, the output of a CSP plant becomes dispatchable, allowing it to supply controllable power on demand to consumers: this is a remarkable advantage compared to other renewable technologies and sources.CSP technology can be combined with any traditional energy system, but the solar input collected by the concentrators is usually used in steam power plants, which are the most mature technology: CSP solar contribution is typically used in Rankine and Hirn cycles with one or two pressure level steam turbine.

In these kind of systems, thermal energy storage (made by tanks filled by molten salt, diatermic oil, PCM…) is usually used as a heat reserve that can be used in the period with lower solar irradiation, to provide heat to the thermodynamic cycle instead of solar direct thermal input.

In the hybrid gas turbine-CSP systems, as the solar input has to pre-heat air before entering the combustion chamber, the role of the thermal storage is quite different (see Barberis et al. [2]).

In this configuration the function of the storage system is to maintain as constant as possible the hot temperature at the heat exchange hot input, which pre-heats the compressed air.

In an ideal system the entire amount of thermal energy captured from the sun is supplied to the gas turbine without the need for a TES: however, since state of the art solar collector can provide heat at maximum 800°C (that are lower than typical gas turbine inlet temperature), an additional heat source is needed.

Power towers can potentially achieve very high operating temperatures over 1000°C, enabling them to produce hot air for gas turbine operation. Solarized hybrid Gas Turbines can be used in combined cycles, composing a Solar Hybrid Combined Cycle yielding conversion efficiencies of the thermal cycle of more than 50% (Fig.1), this being a leap in performance for solar energy conversion.

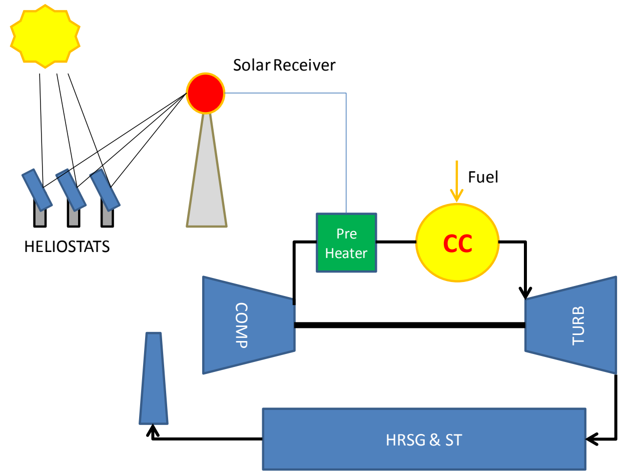

Figure 1 – Solar Hybrid Combined Cycle Plant Layout

A thermoeconomic approach to investigate the optimal condition for sizing and managing such kind of plants has been presented in some recent studies by Augsberger et al. [3] and by Spelling et al.[4], particularly looking at the best solutions for storage and solar field sizes.

Several studies analyzed the potential for the integration of storage into CSP plants. However, the vast majority of studies have focused either simply on the effects of TES on the economics of electricity production. Ravaghi-Ardebili, Manenti et al. [5] built up a dynamic simulation tool to evaluate the performance of double tank molten salt TES in CSP Steam Plants.

Dynamic analysis is used by Traverso et al.[6] for Hybrid – TG CSP plants where the focus is on performance and control of a Solar Hybrid Combined Cycle power plant from a simulation stand point, including the dynamics of a high temperature ceramic honeycomb as thermal storage, while Spelling et al. [7] developed a model of a pure-solar CC power plant to determine the thermodynamic and economic performance of the plant for a variety of operating conditions and super- structure layouts in the region of 3 MWe to 18 MWe. Also, they used this model of multi-objective thermo-economic optimization for both the power plant performance and cost.

Brayton cycle integrated with CSP preheating and TES system is under study by various research institutes (e.g. DOE and DLR [1], [8],[9]), but a power block over 1 MW has not yet arrived at an experimental stage yet.
The TPG (Thermochemical Power Group – www.tpg.unige.it) of the University of Genoa, in collaboration with D'Appolonia SpA, is developing an innovative layout and control scheme to avoid the need for any high temperature valves, thus featuring lower costs and higher reliability, demonstrating it at laboratory scale.
The TES is made by five ceramic honeycomb modules (Fig.3, particular), and it is being integrated with a slip stream from the 100 kW mGT [10] already present on site (Fig.3), while the solar input will be physically simulated with electric heaters.

Figure 2 – The microturbine Test rig being modified for solar hybridization and storage

In this paper a dynamic analysis of the Test rig is presented using original models developed in TRANSEO, simulation tool developed at TPG of the University of Genoa for dynamic and control analysis of gas turbine based energy systems [11]: TRANSEO has its own component library and original libraries for working fluid properties.
The simulations presented here provided the requirements for the Test rig design.

2. HIGH TEMPERATURE STORAGE FOR HYBRIDISED GAS TURBINES

Since the sun is an intermittent source of energy, each of CSP technologies can be operated with fossil fuel as well as solar power and also with thermal input stored during the central hours of the day.
Solar heat collected during the daytime can be stored in concrete, molten salt, ceramics or phase-change materials.
At night or during intermittently cloudy weather conditions, it can be extracted from the storage to run the power block. Thermal Energy Storage (TES) is important for the accelerated market penetration of CSP plants because allows to dispatch the energy stored during the 24h.
Hence thermal storage and hybrid operation with fuels allow CSP plants to provide power on demand, overcoming the limitation due to the intermittence of the solar source.

In this paper an innovative CSP Thermal Storage Layout is presented. This new layout concept, patented in 2013 by the authors, will be tested in the University of Genoa Savona Campus Test Rig [13]. Its dynamic behaviour and its control strategy is described here below.

During the charging phase (Fig.3 – green arrows), the pressurized air coming from the compressor outlet is led by the three-way valve 2 (which is the only mid-temperature regulating valve) through the CRS (where is heated by the collected solar radiance). Operating on the three-way valve 3 (which is an on/off valve), air can bypass the TES system arriving at the combustor inlet or it can pass throughout the TES system (if the solar heat input exceeds the fixed thermal input threshold) thus starting the charging phase. During this phase the pressurized air through the regenerator is cooled while the storage medium is heated. After a certain time (charging period) the regenerator will be charged and the stored solar heat can be used at a later time: this situation is achieved when the temperature at valve 3 overcomes a given threshold.

Once the storage has been charged, it can be discharged operating on the three-way valves 2 and 3. The CRS is bypassed and air goes throughout the regenerator in the opposite direction compared to the charging phase. In this way the air during the discharging phase is heated while the storage medium is cooled, thus realizing the preheating of the compressed air before the combustor inlet.

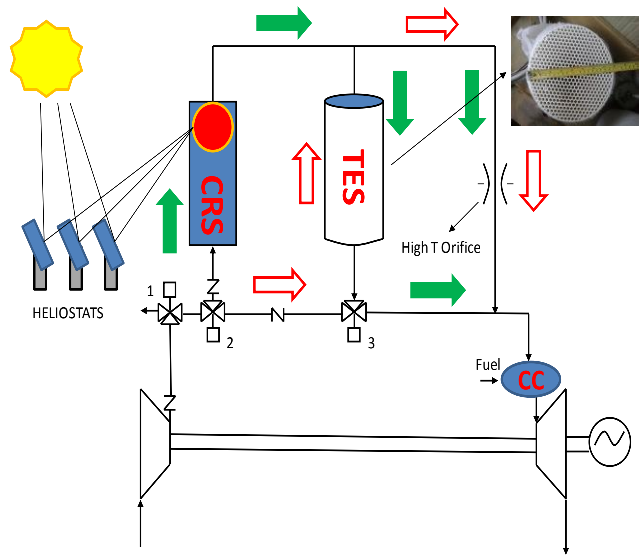

Figure 3 – Schematics of the Hybridised Gas Turbine Storage Plant - Charging (green arrows) / Discharging (red arrows) phases – Particular of the honeycomb ceramic modules.

It should be noted that this plant layout avoids any high temperature valve (800-900°C), expensive and unreliable instruments for this application. Moreover, only one regulating three-way valve (2) and one on/off three-way valve (3) are needed. This result is achieved using the high-T orifice, which is a calibrated variable flange that can be set with a desired pressure drop.
Indeed, the three-way valves are subject to the compressor outlet temperature, at levels where conventional materials can be employed. In this respect, the bottom segment between the compressor and the combustor is called the "cold side" of the plant, while the top segment is called the "hot side" (800-900°C). This solution avoids the use of valves on the hot side, but introduces permanent pressure losses due to high-T orifice.
The high temperature orifice has been conceived as a variable pressure drop device, with two possible positions: minimum and maximum opening. Such openings are used when low or high flow has to cross such an orifice, depending on the operating state in order to control the operating phases of the system.
Moreover, thanks to the use of the high-T orifice, only one regulating three-way valve (2) and one on/off three-way valve (3) are needed.

Within the regenerator, two threshold temperatures, a low and a high one, can be defined to manage the switch between the charging and discharging phases.
In this work, at simulation level, the temperature in the low layer of the regenerator (cold side), near the three-way valve, should not exceed 430°C. The temperature in top layer of the regenerator (hot side) should be higher than 650°C before starting the discharging phase of the storage.

Such a concept promises low cost and high reliability, despite introducing permanent pressure losses due to high-T orifice. The main additional pressure losses due to the solar components at the design point are:

- 1% on three-way valves 2 and 3
- 2% on CRS
- 7% on TES
- 4% at the high-T orifice (charging phase),
- 1% at the high-T orifice (discharging phase)

Such pressure drops vary depending on the operating conditions, according to conventional pressure drop relationships [6] [10].

3 PLANT DYNAMIC MODEL

In order to verify, at theoretical level, the goodness of the proposed solar system integration, a campaign of numerical simulations was carried out. The plant was modelled using the TRANSEO [10] simulation tool developed at TPG of the University of Genoa for dynamic and control analysis of gas turbine based energy system.
The results of this campaign of simulation derived from a previous work described in [6] in which the system SGTU (Solar Gas Turbine Upgrade) was joined to a 12 MWe gas turbine plant. The present paper will study the interaction between the solar system upgrades and a small size mGT.
In particular, it was considered the modified mGT Turbec T100 [12] available at the TPG laboratory of Savona.
The machine is equipped with a thermal recuperation system of the exhaust gases and it is capable to deliver 100 kWe of electrical power against the 330 kWt necessary to the combustor (nominal conditions).
The mGT can operate at constant or variable rotational speed: in this work constant speed has been chosen (and nominal power output).
The SGTU was then placed between the recuperator and the combustor so as to obtain the actual solar preheating of the pressurized air.
The heliostat field, emulated by electrical heaters in the Test rig, has been sized so as to deliver to the CRS a maximum heat flow of 200 kWt which represent approximately two thirds of those needed to the combustor to supply the nominal power. This value has been chosen according to economic considerations on the cost of reflecting surfaces as well as the need to avoid too much lower load of the combustor under conditions of high radiation. In the activation phase of the CRS, the three-way valve 2 is piloted by providing an air flow towards the receiver in order to maintain the fluid temperature at 800°C. The ceramic modules constituting the TES were designed to operate with the characteristic times of charge and discharge of about 30 minutes, if operating in nominal conditions (CRS exit temperature of 800°C and TES charging flow rate of 0.4 kg/s).

3.1 Development of the SGTU control strategy

The two basic components of the system are the CRS and the TES, it is therefore natural to think that the control system of process valves is based on two parameters: the level of heat flux picked up and the state of charge of the thermal storage.
In particular, three levels of solar heat flux have been identified: low power (LP) (<30 kWt), medium power (MP) and high power (HP) (> 120 kWt). The state of the TES is estimated by the evaluation of the temperatures at both regenerator ends..
Five operating states have been defined, as explained in the following. . Basing on such operational states, Table 1 presents a summary of the transition logic for enabling the different states, basing on TES state of charge and level of irradiation..

	LP	MP	HP
TES charged	4	3	1
TES empty	0	1	2

Table 1 – Activation logic of the operational states: if the row an column headers are verified, then the related state can be enabled.

Status 0: Bypass SGTU
This state represents the standard operation of the mGT; it is implemented when the captured solar power is not economically sufficient for the activation of SGTU. Both the three-way valves switch in order to stop the flow of air towards the components CRS and TES.

Status 1: TES bypass
This state represents a first mode of use of solar energy, it is implemented in the intervals where it is not necessary to activate the TES. This occurs in two possible situations:

- Medium Power condition with discharged regenerator and a low flow rate at the CRS that can't charge and activate the TES
- High Power condition with fully charged regenerator (so it's not needed to charge the TES)

The first three-way valve is controlled to maintain the Tout at the CRS, the flow rate in this component is then sent to the branch of the by-pass where the variable section orifice will present the max opening. The second valve interrupts the flow to the TES sending it to the combustor.

Status 2: Pilot Charge
This state represents the charging mode of the TES. The three-way valve 2 is also in this case piloted, the flow rate flowing in the branch of the CRS is thus proportional to the power captured, this flow is finally divided between TES and the bypass branch, where the orifice has a minimum opening. This state is usually activated only in the HP intervals.

Status 3: Pilot discharge
This state represents a mode of combined use of solar power of the receiver and the energy stored in the TES. This state is implemented when the regenerator is charged and solar power is adequate for activation of the CRS (MP). The three-way valve 2 delivers a flow proportional to the power captured in the CRS, the remainder is sent through to the three-way valve 3 to the TES for discharging. The orifice is fluxed with the whole flow drawn from the mGT and it has the maximum opening in order to mitigate pressure losses.

Status 4: Full discharge
This state is used to discharge thermal energy from the TES; it is implemented in the LP ranges, TES charged, i.e. when it is not possible to use the CRS. The three-way valve 2 stops the flow to the CRS while the valve 3 switches to direct the whole flow towards the TES. In this case, the variable section orifice also presents the maximum opening.
If the TES is totally charged and no electricity is request, the TES discharges itself slowly and autonomously thanks to the action of the high T orifice if this interruption is not a start&Stop, in that case the TES is kept charged keeping close valve 3.

4 DYNAMIC SYMULATIONS

It has been necessary to generate two different numerical model of the plant SGTU and the mGT. The simulative campaign focused, during its initial stages (Test 1), on the solar apparatus in order to verify the control strategy. Secondly the SGTU was joined to the machine (Test 2) to obtain results on the dynamic behaviour of the hybrid plant, studying it in a different simulation time of 4,5 hours. The following paragraphs will briefly describe the main stages of work and the results obtained.

4.1 Test 1 results

This Test relates only to SGTU; it has therefore been necessary to set the correct fluid-dynamic boundary conditions at the system, in particular, these values were calculated using a previous simulation of the standard mGT operating in nominal conditions. Test1 uses a profile of direct solar radiation (and hence the solar power captured) without shadowing phenomena (Fig.4).

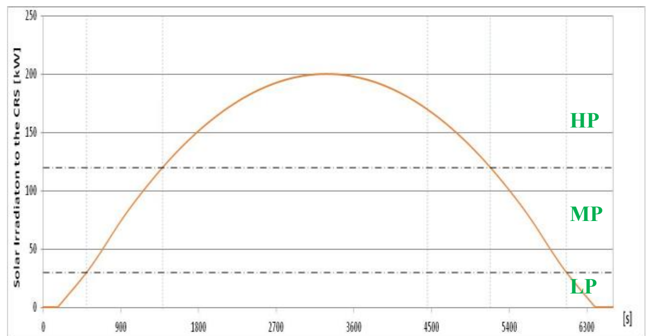

Fig.4 - Solar Thermal Flow to the CRS

With the aim of maintaining short computational time, a simulation time of approximately 2 hours has been set, compared to 8-10 hours of real daily solar cycle.
The initial condition of the TES is constituted by a constant temperature profile along the 'longitudinal axis' and equal to the value at the recuperator output (650°C): this condition is suitable to simulate the effective state of the regenerator after full discharge. Once defined all boundary conditions, it has been possible to obtain the first results on the behaviour of SGTU with changes in irradiation conditions (Fig.5).
From the graphs we can see that during the transition from LP to MP, the system switches from state 1, which is the standard operating condition of the mGT, to state 2, activating the CRS to use the solar power directly for the air pre-heating. To prevent destructive overheating of the CRS, the component is fed by a minimum when disabled (states 1 or 4). When HP threshold is crossed, state 3 of TES charging is enabled. We observe that in this state, the flow through TES results about an half of that evolving in the CRS (which is proportional to the collected solar power).

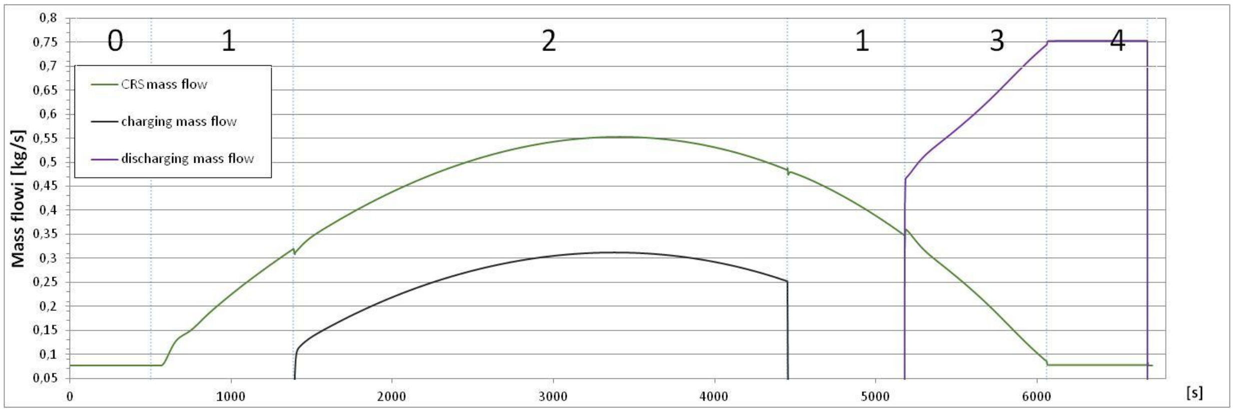

Fig.5 – CRS and TES mass flows

This distribution of flow is created due to the partial closure of the cross section of the calibrated orifice located in the bypass branch. Once the TES is charged, i.e. when the temperature of its hot extreme exceeds the threshold value, the system switches operation state returning to state 1, in which the TES is excluded.

In the phase characterized by decrease in captured power and particularly when there is the change from HP to MP (with TES charged), the system responds reaching state 4, this state using simultaneously the CRS and TES in discharge. The flow in TES is, in this case, equal to that delivered by the machine less the portion sent to the CRS: so, it is clear that CRS and TES mass flow rates have opposite behaviour.

In the end of the simulation period, the CRS receive a low solar thermal flow and it responds by disabling the CRS and the air is preheated by the TES thermal input.

4.2 Test 2 results

This Test involved the study of the assembled system consisting of SGTU and mGT with particular interest in the response of the plant to variations in radiation picked up by the CRS.

Therefore, a profile of solar power captured by the CRS was set up greatly disturbed (Fig.6), aimed to simulate the effect of passing clouds shadowing direct irradiation; the duration of the simulation has been increased to 4,5 hours to still allow the TES to reach full charge in between the disturbances.

The control system of the electric power delivered from the mGT, which operates on the fuel flow rate, is set to maintain a constant power (80kW) and equal to about 80% of the nominal.

This choice is necessary to avoid that the additional pressure drops of the SGTU cause too high TOT, both for the expander and the recuperator.

In order to show and underline the most relevant results, there will be proposed graphs related to the last phase of the simulation period with a solar irradiation similar to a typical afternoon solar profile and in order to have a comparable simulation period with the test 1 configuration.

The first graph (Fig.7 – upper part) shows the trends of the heat flux received by the CRS and the one developed by the TES; we can see that the former is proportional to the direct radiation incident on the reflectors, and it is therefore almost zero during the shadowing disturbances. The solar heat flux collected by the CRS can be used to heat pressurized air or it can stored in the TES. During HP periods (regenerator discharging - state 2), the system activated the TES absorbing heat from the preheated air.

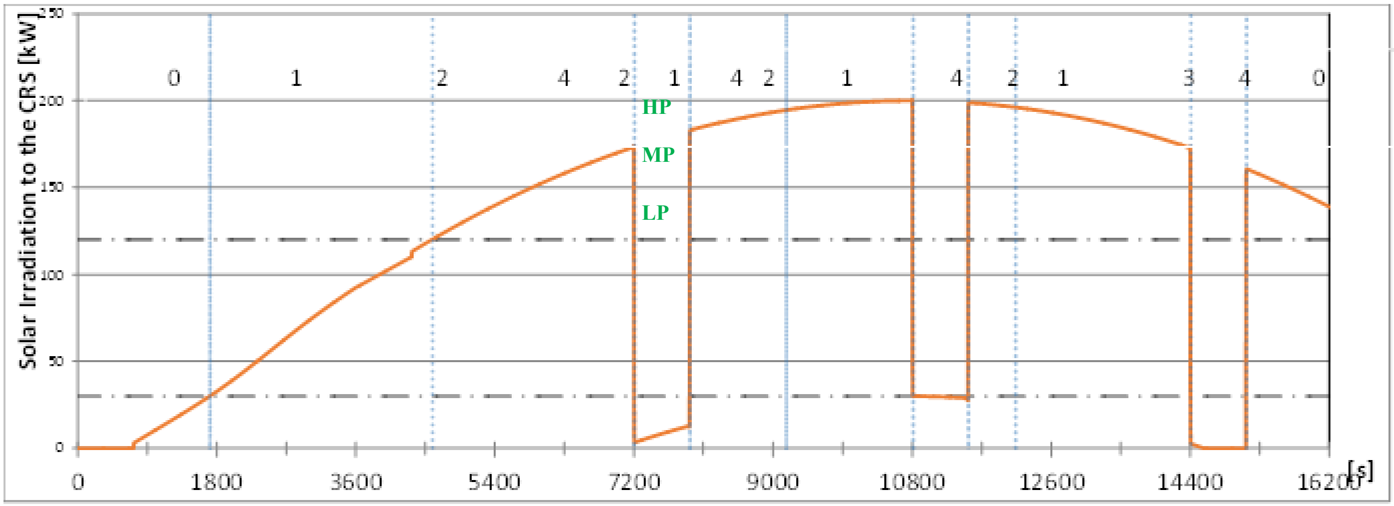

Fig.6 - Solar Irradiation with disturbances to the CRS

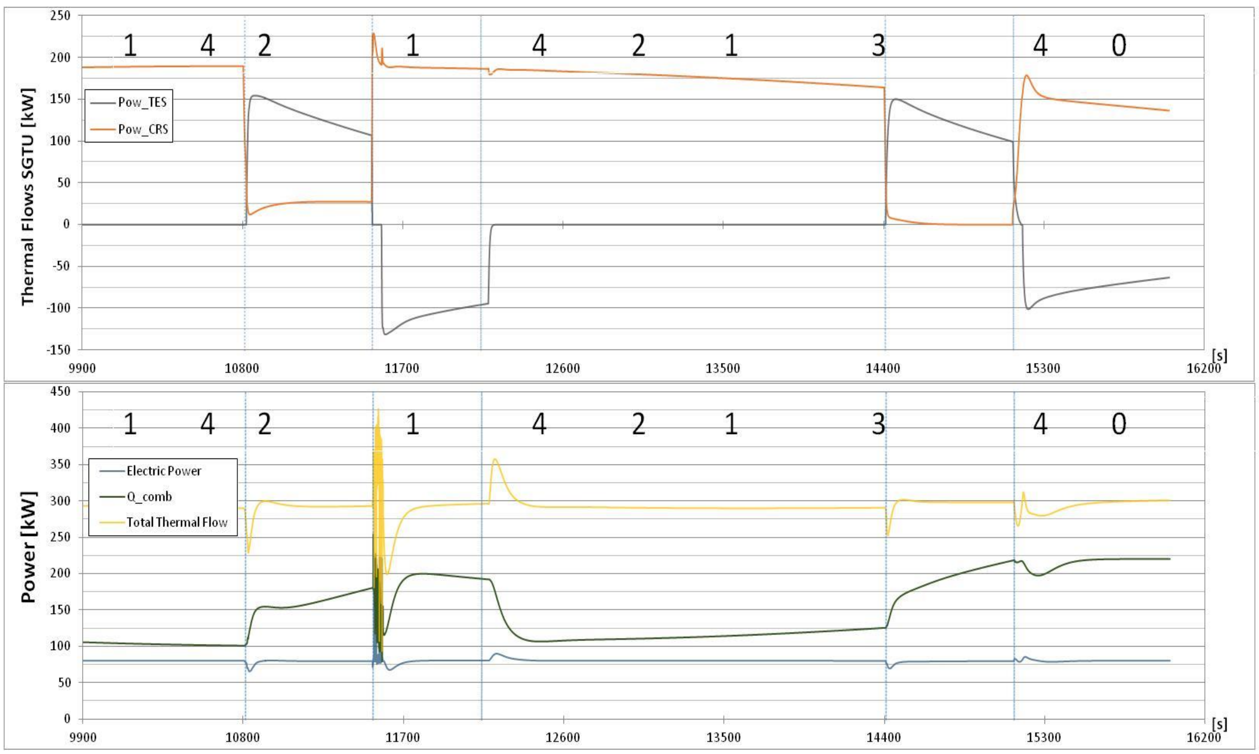

Fig.7 - Electric power, TES, CC and CRS trend in simulation time

By contrast, during disturbance phenomena, or more in general in case of prolonged LP irradiation, the system discharges the TES (state 4) releasing heat to the plant.

In the last phases of the simulation, during MP conditions, the system moves to the piloted discharge condition of the TES. As it can be observed, comparing this situation to the full discharge one, in this case the heat release and the discharge phase are shorter.

In the second chart (Fig.7 - lower part) the trend of heat flux provided by the combustor, the total flow required by the operation of the machine and the electric load delivered are shown.

First of all it should be noted that the SGTU implies a worsening of the thermal efficiency of the mGT, due to additional pressure losses as it can be seen in fig.7 - lower part passing from phase 3 to phase 4 where, even if the TES contribution is present, the heat provided by the fuel

is definitely higher than in the periods of CRS contribution.
Anyway, a clear decrease in the consumption of fuel is observed in all phases of operation, in particular the minimum values are found in the intervals of operation HP where the TES is already charged (state 1), under these conditions the consumption is about one third compared to standard operating conditions.
During the bypass phase of the SGTU system there aren't decreases in fuel consumption, even if pressure drops are present.
Fuel consumption in other states of operation is higher because:

- During the charging phase (state 2) the combustor receives only part of the flow received by the CRS as a part is absorbed by the TES (unless the TES is fully charged: in such a case fuel consumption is reduced by about two thirds);
- During the pilot discharge phase (state 3), heat contributions from both the CRS and what it has been stored in the TES can be used, in order to admit low consumption particularly during the early phases when the solar flux is relatively high and the TES is full load with a high temperature thermal contribution;
- During the full discharge phase (state 4) only the energy stored in the TES is used, but this thermal input is available at a lower temperature than the CRS exit.

However it's important to underline that the change of operating state from TES charging to TES discharging is critical as it may bring the compressor close to the surge line and eventually to instable behavior,.

5 CONCLUSIONS

The dynamic simulation of the integrated SGTU-MGT system brought the following results:

• Fuel consumption is significantly decreased; along the Test 2 case study a Solar Share Factor (SSF) average of 0.35 was obtained. SSF peaks at 0.65 in the intervals with high direct irradiation in which the TES is charged;

• The SGTU produces non-negligible pressure losses, particularly when a high flow rate passes through the TES and / or the bypass branch; in this respect, the variable area high temperature orifice helps in mitigating overall pressure drops;

• Change of operating state from TES charging to TES discharging is critical as it may bring the compressor close to the surge line and eventually to instable behavior, as shown in Test 2; a careful scheduling of valve operation is required to avoid compressor surge;

• The additional pressures losses due to the SGTU system reduces the turbine nominal power; in the present study the nominal power was decreased from 100kW to 80kW, retaining a satisfactory safety margin on temperatures (TIT and TOT) and compressor surge;

• The inlet temperature to the CC is highly variable with the external conditions of direct solar radiation and the operating conditions of the SGTU, this being a challenge for the combustor itself.

Basing on such considerations, the following future developments are envisaged:

• Analysis of surge margin in all operation phases, to improve valve scheduling and, in the end, the control logic as the simulations showed some surge problems (Fig.7 – lower part) that can be avoided thanks to a careful scheduling of valve operation;

• Study of a regulating three-way valve 3, to continuously control the flow through the TES and helping in keeping as constant as possible the overall pressure drops; such a valve could be used to control the combustor inlet temperature, as well;

• Improve the estimation of the state of charge of the TES. This can be achieved by using a number of temperature measurements along the major axis of the TES in order to identify the level of thermal stratification.

In conclusions, TRANSEO dynamic analysis proved that the presented innovative high temperature storage layout can guarantee a robust behaviour of the system, avoiding the use of hot valves and promising low cost and high reliability, despite introducing permanent pressure losses due to high-T orifice.

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