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A simulation tool for concentrated solar power based on micro gas turbine engines

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ABSTRACT

In the scenario of the small scale 3–35 kWe concentrated solar power plant based on point receiver technologies, the dish-Stirling configuration is one of the most commonly adopted one. New and clean efficiency of these Stirling engines is typically of 30–40%. Yearly average efficiency, during the system operations, is significantly reduced to 10–15% due to the Stirling engines high maintenance costs and poor reliability issues. These drawbacks limit the small scale dish-Stirling engines market attractiveness. The adoption of cheap, reliable and widely available engines, such as micro gas turbines is a promising solution for substituting Stirling engines since it ensures constant performance over time. Since micro gas turbines for concentrated solar power plants equipped with dish concentrator have not been widely deployed, the development of a plant simulator is helpful for predicting the overall concentrated solar power plant performance and for optimizing the plant operations under different boundary conditions. The plant simulator is aimed to demonstrate the economic viability and the technical feasibility of dish-micro gas turbine systems.

The paper includes the methods for developing a simulation tool for solar dish – micro gas turbine applications. The solar concentrator, receiver/absorber, micro gas turbine, high speed generator and power electronic systems have been modelled and the plant simulator has been set-up by means of a quadratic programming technique. The simulator has been used to perform steady state simulations for predicting the performance and for ensuring a safe and reliable power plant operation when the direct normal irradiation changes. The results for a net generated power of about 6 kWe have shown a nominal peak efficiency of about 10%, making this micro gas turbine solar plant layout market attractive.

1. Introduction

The need for environmentally friendly energy systems has led to the exploration of a wide scenario of renewable energy fed power plants. Geographical location as well as political and environmental contexts offer the possibility of choosing the most suitable energy converters, such as wind turbine, photovoltaic and concentrated solar power (CSP) [1]. Chu et al. [2] have selected five of the most commonly studied and discussed solar technologies and reviewed their structure, performance, advantages and drawbacks. CSP plants based on linear receivers produce a hot heat carrier or steam directly. For temperatures of 400–550 °C, these systems have demonstrated an overall annual solar efficiency ranging from 8% to 15% when equipped with engines of efficiencies of about 30–40%. A list of parabolic trough power plants in the range of 50–100 MWe arranged in a combined cycle [3]. Behar et al. [4] present an economic analysis based on localized cost of energy, which demonstrates that better performance are achieved in larger the hybrid plants. A 10 MWe power plant, indeed, can have a localized cost of electricity of 0.108 h/kWh with twice the annual efficiency and a lower cost than a solar tower system of 4 MWe. CSP plants are also based on point receivers. Tower systems are suitable for large power range (100–150 MWe and higher). They should be operated with steam cycles and/or gas turbines and are capable of reaching 45–50% efficiency if set-up in a combined cycle. The other technology based on point receiver is the parabolic solar dish. Dish systems have reflecting surfaces ranging from a few square meters up to 450–500 m^2 in a single unit as reported by Keck et al. [5] and Devlin [6]. In the context of small farms and distributed generation, the solar dish based CSP plants of few kWe (3–35) are equipped with the Stirling engines whose peak nominal efficiency is about 30–40% when operated at around 650–700 °C as discussed by Ahmadi et al. [7]. In the same work [7], it is discussed how the availability and reliability of such engines present major drawbacks

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Nomenclature

d	diameter [m]
DNI	direct normal irradiation [W/m^2]
f	factor [–]
h	enthalpy [kJ/kg]
n	shaft speed [rpm]
P	power [kW]
p	pressure [kPa]
Q	heat power [kW]
S	surface [m^2]
T	temperature [°C]
TIT	turbine inlet temperature [°C]
W	work [kJ/kg]

Greek Symbols

α	absorptivity
β	pressure ratio
η	efficiency, merit parameter
χ	reduction factor for solar irradiance
θ	geometrical angle [°]
φ	geometrical angle [°]
Φ	heat flux [W/m^2]
μ	corrected mass flow
ν	corrected speed
ε	effectiveness, emissivity
Δ	difference, unbalance

Subscripts and abbreviations

0, 1, 2, …, N	station number
AUX	auxiliaries
BB	black body
C	compressor
CF	concentration factor
CSP	concentrated solar power
E	expander
EL	electric
ENG	engine
gl	global
HSG	high speed generator
HTD	heat transfer device
i	inlet, isentropic
id	ideal
M	mechanical
MGT	micro gas turbine
ML	mechanical loss
NA	non-adiabacity
NET	net
o	outlet
OBjF	objective function
R/A	receiver/absorber
r	reference
SC	solar concentrator
SH	shape
SN	sun number
W	window
WF	working fluid

to their market attractiveness owing to the high maintenance costs. This is due to the highly pressurized working fluid (WF) – helium and hydrogen – that leads to technical problems (i.e. seals, leakage of the WF) and to an increase in the complexity of the plant arrangement and operations (and thus higher cost) owing to the change in boundary conditions. Some research works conducted by different authors such as Elgendy [8] and Kussel et al. [9] report that for increasing the dish – Stirling efficiency an increase on the operating temperatures and pressures should be adopted but consequently the leakage issue becomes more relevant, as demonstrated by Chen et al. [10].

In order to avoid such problems, the adoption of cheap, reliable and highly available energy converters, such as micro gas turbines (MGT), is a promising solution for substituting Stirling engines, ensuring consistent performance over time. For larger solar dish diameters [5], CSP plants based on MGT show a 20–30% efficiency as stated in Capstone product catalogue [11]. MGTs are competitive in solar dish applications because they do not present deep maintenance issues and significant performance deteriorations even if operated in harsh environments like the desert and sea side. The adoption of turbomachinery based energy converter units as discussed in the work of Horlock [12] and Hendricks et al. [13], also differently arranged, shows high reliability and operation flexibility. Jonsoon et al [14] present various water injected gas turbine solutions for demonstrating how this technique helps in increasing the lifetime of the hot part components. These advantages, coupled with the lower cost of MGTs, especially if taken from the automotive technology, make the dish-MGT CSP plant a viable solution for producing electricity conveniently, as reported by Cerri et al. [15]. Trabalesi et al. [16] discuss that the adoption of a properly sized energy storage tank brings to higher revenue and higher turbine reliability, with the operating conditions of the machine kept as close as possible to the nominal value. An average yearly efficiency increase of 4% has been observed for the presented system, as discussed by Wang et al. [17].

For optimally designing this type of power plants, the adoption of homemade simulation tools brings promising solutions due to the fact that most of the components are designed and installed as prototype, especially looking at the small scale scenarios. The development of a CSP plant simulator is helpful for exploring the economic viability and the technical feasibility of a dish-MGT solution in the small-scale renewable energy scenario for several reasons. By means of this simulation tool, it is possible to predict performance due to the boundary conditions changes. The CSP plant simulator is used for the component's design, part load analysis and for optimal control strategy rules definition, according to the methods proposed by Cerri et al. [18,19]. The CSP plant simulator also helps to avoid exceeding the threshold values of temperatures and pressures, ensuring safe and stable operating conditions owing to the direct normal irradiation (DNI) variability when transient behaviour operations are considered. Indeed, CSP plants equipped with turbomachinery based engines, such as steam cycles, organic Rankine cycle and Brayton cycles, have shown that the oscillations of the radiant power produce pulsations on the trust bearing, which causes fatigue damages, as proven by Woodard and Hudson [20] and Lave and Kleissl [21]. Available commercial tools for power plants simulation, from websites [22–24], allow cycle calculations, sizing of plant components, off-design analysis and optimum plant management and diagnosis. These tools are addressed for larger power plant sizes and they do not seem to be the best choice for replicating CSP plants of only few kWe. Specific tools for CSP plants has been developed by Sandia [25]. Tools including also Stirling engines are available as presented by Kaddour et al. [26].

At the present state of the art, dedicated software for the above purposes have not been deployed for dish-MGT CSP plants and it is one of the motivations that have led the authors to explore the development