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Comparison of potential control strategies for an impinging receiver based dish-Brayton system when the solar irradiation exceeds its design value

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ABSTRACT

Potential control strategies for an impinging receiver based dish-Brayton system have been presented for protecting the key components from the risks of overheating when the solar irradiation exceeds its design value. Two of them are selected for a detailed study: changing the effective diameter of the shading device and changing the inlet temperature. A rope-pulley shading device is developed for controlling the shading area in the center of the dish, and the change of the inlet temperature is achieved by applying a bypass at the cold side of the recuperator for reducing the heat transfer rate. Both control strategies can manage the peak temperature on the absorber surface within 1030 °C with an outlet temperature fluctuation between −4.1 and 15.1 °C, so that the impinging receiver can work for long time at any solar direct normal irradiance value. Furthermore, the temperature differences on the absorber surface are between 137.1 °C and 163.8 °C. The cases that are achieved by changing the shield effective diameter are significantly lower (11–26 °C) than the corresponding cases that are achieved by changing the inlet temperature.

1. Introduction

Parabolic dishes are considered as the most efficient concentrating solar power (CSP) technology, because they can offer much higher concentration ratio than other CSP technologies [1,2]. By integrating with micro gas turbines (MGT), these solar hybrid dish-Brayton systems have great potential in obtaining stable power outputs independent of solar energy variations, improving the overall solar-to-electrical power generation efficiency and reducing the costs of solar dish systems [3]. The technical and economic feasibilities of hybrid solar Brayton technologies have been proved experimentally by Buck et al. [4], Heller et al. [5], Dickey [6] and Korzynietz et al. [7] for small-scale central tower systems. Furthermore, the Brayton cycle can also be used as the first stage cycle of a combined cycle to achieve a higher solar-to-electric net annual average conversion efficiency [8]. The second stage cycle can be a Rankine cycle [9], Stirling cycle [10], supercritical CO2 cycle and so on [11].

In a typical solar dish-Brayton system, the receiver and the MGT are the two key components. Especially critical is the receiver where the concentrated solar irradiation is absorbed and transferred to the working fluid in the form of heat. Considering the temperature and the pressure requirements from the MGT, the solar receiver has to be designed with an ability in offering outlet air with high temperature (700–1100 °C) and high pressure (3–10 bar) for long time [12,13]. Considering the temperature difference between the absorber and the working fluid (compressed air), the absorber of the receiver usually has to work at a higher temperature than the outlet air temperature [14]. Therefore, it is considered as one of the limiting components for improving the system life and efficiency. In the design procedure of a CSP system, the design direct normal irradiance (DNI) is one of the most important input parameters that can decide the final sizes of the receiver and the MGT. For a fixed dish size, a high design DNI value would make the system safe, but the receiver and the MGT would be oversized; a low design DNI value would lead to an oversize of the dish, and the receiver and the MGT might be destroyed when the real DNI exceed the design DNI value. Generally, the design DNI of a typical solar-thermal plant is between 800 and 950 W/m^2 which is always below the peak DNI level of the plant location [1,15].

Although several projects focus on small-scale central tower power based solar Brayton technologies have been funded by the European Commission and the US Department of Energy so far, the dish-Brayton technology is still a relatively new research area [16]. Theoretically, a local peak DNI value of 1000 W/m^2 can be used for designing a hybrid dish-Brayton system, and the stable power outputs can be achieved by changing the solar share flexibly according to the solar energy variations [17]. However, the proportion of the time that the DNI can approach the local peak DNI value is very small even for the global sun belt region [18]. Therefore, for a hybrid dish-Brayton system designed

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Nomenclature

A	area, m^2
C_p	specific heat, J/(kg·K)
d	diameter of the nozzle or orifice, mm
D	diameter, m
h	enthalpy, J/kg
I	solar direct normal irradiance, W/m^2
k	heat conductivity, W/(m·K)
$\dot{m}$	mass flow, kg/s
P	pressure, Pa
$\dot{Q}_{sol}$	concentrated solar radiation flux, W/m^2
T	temperature, °C
y_1	distance of the first grid node normal to the wall, m
y^+	dimensionless wall distance of the first grid node near the wall

Greek

ε	emissivity
η	efficiency
ν	kinematic viscosity, m^2/s

Subscripts

amb	ambient
cb	combustor
cp	compressor
d	parabolic dish
des	design value
h	center hole
i	inlet
o	stagnation point
opt	optical
real	real value
ri	receiver inlet
ro	receiver outlet
s	shading device
t	thermal
ti	turbine inlet

Abbreviations

CFD	computational fluid dynamics
CSP	concentrating solar power
DNI	direct normal irradiance
DO	discrete ordinates radiation model
EFMGT	externally-fired micro gas turbine
LCOE	levelized cost of energy
MGT	micro gas turbine
PID	proportional–integral–derivative controller
RANS	Reynolds-averaged Navier-Stokes
SST	shear stress transport
TIT	turbine inlet temperature
UDF	user design function

base on the local peak DNI value, the MGT should work under an actual DNI level below its design value at most of its operating time. It also means that less solar-derived thermal energy is supplied to the heat engine than in design conditions, and fossil fuel has to be consumed to fill the ’gap’ for the purpose of keeping a stable electrical power output [1]. In such a system, though the solar energy can be utilized efficiently, the solar share would be relatively low. In order to enhance the solar share of the system and reduce the system levelized cost of energy (LCOE) to a lower level, an optimal design DNI, usually lower than local DNI peak, should be calculated during the design procedure of a hybrid dish-Brayton system [16]. It also means that in some days during a year, usually at noon, the local DNI value would exceed the design value of the system. This engineering problem can be easily solved by changing an effective number of the heliostats in a central tower CSP system [19]. However, for dish system, the available solutions can only be achieved by defocusing the dish [16] or increasing the power of an extra cooling fan to take the extra heat when the local DNI level exceeds its design value [20]. For the defocusing strategy, the good solar condition can’t be used for power generation at the best hours for solar energy harvesting. For using a cooling fan, although the engine can generate power at its design conditions, the electrical energy consumed by the fan would greatly limit its net power output. Hence, it is of great important to develop an effective control strategy to ensure that the receiver and the MGT can still work stable when the local DNI exceed the design value of the hybrid dish-Brayton system, without introducing any significant cost and annual efficiency loss. However, in the published literature on the hybrid dish-Brayton technologies, the most research was on the thermodynamic modelling and system analysis level [21,22]. For practical application research, especially the control strategy research for safety running, it is still rare so far.

In the authors’ previous study, a high temperature stainless steel (253 MA) based impinging receiver was successfully developed based on the parameters of a EuroDish and a Compower® MGT [23]. With the help of an indoor high flux solar simulator, this impinging receiver concept has been validated to be able to offer an outlet air temperature of 810 °C with a radiative-to-thermal efficiency above 74% [24]. Since the Compower® MGT is a typical externally fired micro gas turbine (EFMGT), the combustion takes place outside the cycle at atmospheric pressure and the compressed air is heated up to the required turbine-inlet -temperature (TIT) through a high-temperature heat exchanger. In this type EFMGT design, the flue gas is not directly contact with the turbine, so various fuels and heat sources can be used, such as coal, biomass, biomass gasification gas and solar energy [25]. Moreover, since the combustion process takes place outside the cycle, the boundary conditions for the combustion are independent from the working parameters of the cycle. The combustion is stable and easy controlled by changing the fuel flow rate. Hence, an EFMGT is easier to be integrated into a hybrid solar Brayton system.

In this paper, the main objective is studying the performances of various control strategies for protecting the key components of a solar dish-Brayton system when the real DNI value exceeds its design value. For high temperature air receiver designs, the absorbers are always working at conditions that close to the materials’ limits. Any temperature increase in the absorber peak temperature would be a challenge to the absorber. Furthermore, for a typical dish-Brayton system, the receiver is integrated between the recuperator and the turbine, an increase in receiver outlet temperature could lead to an increase in the TIT of the MGT, which could damage or reduce the working life of the MGT. For this purpose, the receiver outlet temperature and the peak temperature on the absorber are two key parameters which are even more important than the receiver efficiency. In total, four different potential control strategies are proposed, analyzed and compared. Finally, two of them are selected for a more detailed study with the help the combination of the non-sequential ray-tracing software FRED® and the computational fluid dynamics (CFD) software ANSYS FLUENT® with user-defined functions (UDFs). In this model, the ray-tracing software is used for obtaining the radiative boundary conditions that are inputted to the conjugated heat transfer model as a thin film heat source boundary condition with the help of UDFs [26].

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