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Experimental and numerical performance analyses of a Dish-Stirling cavity receiver: Geometry and operating temperature studies

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ABSTRACT

Higher performance cavity receivers are needed to increase the competitiveness of solar power plants. However, the design process needs to be improved with more relevant experimental and numerical analyses. Thereby, the performance of four different Dish-Stirling cavities is investigated experimentally analyzing the influence of the cavity aperture diameter and shape at various operating temperatures. Temperatures inside the cavity receiver were collected together with the electrical power produced by the engine-generator. Then, a thermal system simulation was modelled and a comprehensive multi-parameter and multi-operation validation was performed. To improve this validation, the temperature distribution across the receiver tubes was analyzed in order to relate temperatures on the irradiated region with the non-irradiated one, where thermocouples can measure. The simulations were later used to obtain cavity receiver efficiencies, temperatures and loss breakdowns. The results show that the cavity receiver must be studied in optimization processes in conjunction with the other system components. Moreover, the reverse-conical cavity was found to be more efficient than a nearly cylindrical shape. Regarding the cavity receiver thermal losses, radiation and natural convection present similar contributions in the system under study. Finally, it was found that thermocouples installed on a non-irradiated region can be used to obtain peak receiver temperatures if the measurements are rectified by a correction value proportional to the DNI.

1. Introduction

Concentrating Solar Power (CSP) technologies are becoming increasingly important as they can produce renewable and dispatchable electric energy. Among them, Dish-Stirling Systems (DSSs) have shown great potential (Monné et al., 2013) but need further development to become competitive within the energy market. One of the most critical components of this technology is the solar receiver, which operates under high solar irradiances reaching the highest temperatures of the system. A proper design of the solar receiver can increase the system efficiency and lifetime while keeping the component cost constant, which would reduce the plant levelized cost of electricity.

Over the last decades, multiple experimental papers have been published studying the performance of cavity receivers (CRs) for parabolic dishes. Most of these papers focus on the analysis of the CR thermal efficiency for a single receiver concept, i.e. (Hischier, 2012) and (Poživil et al., 2015) studying pressurized-air receivers, and (Pye et al., 2017) and (Reddy et al., 2015) testing non-Stirling directly illuminated tubular receivers. (Kribus et al., 2001) includes in their measurements more data about the absorber temperatures and (Hischier et al., 2012) also presents experimental results of various cavity receiver configurations. For DSSs, only general measurements under real operating conditions have been collected from multiple existing systems, such as in (Lopez and Stone, 1992) and (Mancini et al., 2003). The collected data mainly consist of the electric generation of the system at various Direct Normal Irradiances (DNIs) but the performance information of the CR is very limited. (Reinalter et al., 2008) shows further results analyzing the flux distribution created by the dish on the CR, and calculating the thermal loss breakdown. It can be observed that only (Kribus et al., 2001) and (Hischier et al., 2012) measure CR operating temperatures, which are necessary for an accurate analysis and optimization of the CR. However, both experiments analyze volumetric receivers, leading to a lack of experimental data of the CR operating conditions for DSSs. Moreover, all Dish-Stirling tests mentioned above were conducted outdoors, consequently presenting a large dispersion of the data due to non-controllable experimental boundary conditions. Unlike them, (Aksoy et al., 2015) couples a Stirling engine with a solar simulator, but with a thermal power of only

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Nomenclature

Abbreviations

CNRS	Centre National de la Recherche Scientifique
CR	cavity receiver
CSP	concentrating solar power
DNI	direct normal irradiance
DDS	Dish-Stirling system
ENEA	Italian National Agency for new Technologies
FEA	finite element analysis
HFSS	high-flux solar simulator
KTH	royal institute of technology
RT	ray-tracing
TC	thermocouple
WF	working fluid

Symbols

A	area [m^2]
A_0	dimensionless fluid displacement [m^2]
b_i	constant value (exponent) [–]
B_i	constant value [–]
D	diameter [m]
F	view factor [–]
G_λ	spectral irradiance [W/m^3]
Gr	Grashof number [–]
h	convection coefficient [W/m^2]
J	radiosity [W/m^2]
k	thermal conductivity [W/m-K]
L	length [m]
Nu	Nusselt number [–]
$\dot{q}$	flux [W/m^2]
$\dot{Q}$	power [W]
r	radius [m]
Re_ω	kinetic reynolds [–]
T	temperature [K]

Greek symbols

α	absorptance/absorptivity [–]
Δ	increment [–]
ε	emittance/emissivity [–]
η	efficiency [%]
θ	tilt angle [°]
λ	wavelength [nm]
σ	Stefan-Boltzmann constant [W/m^2-K^4]

Subscripts

amb	ambient
ap	aperture
C	cooler
cd	conduction
cv	convection
ge	generator
H	heater
i,j	node denotation
inter	interception
lamps	from the solar simulator
max	maximum
me	mechanical
ra	radiation
rec	receiver
ref	reference
refl	reflection
st	Stirling
sys	system
t	total
w	cavity receiver wall
WF	working fluid
ω	oscillating

1 kW and a main focus on the Stirling engine performance analysis instead of the CR.

Unlike experiments, the literature of CR design simulations is very extensive, analyzing and optimizing the critical design parameters defined in (Harris and Lenz, 1985). Some studies focus on the optical analysis, i.e. (Shuai et al., 2008); (Li et al., 2013) and (Wang et al., 2013), which mainly analyze the impact of the CR geometry and the dish properties. Nevertheless, these studies miss to efficiently couple optical and thermal models to predict the total performance of the dish-CR system, which is essential to find an optimum CR design. More detailed optical-thermal models and optimizations were developed for pressurized-air (Hischier et al., 2015) and volumetric (Aichmayer et al., 2018) receivers, and for parabolic dish tubular receivers (Asselineau et al., 2015); (Pye et al., 2015) and (Loni et al., 2016). Nonetheless, these studies are not applicable to DSSs since they do not account for the constrained tube layout imposed by the Stirling engine design, thereby becoming the definition of active (receiver) and non-active (cavity) areas a key design feature. Among the models for DSS, (Fraser, 2008) and (Nepveu et al., Jan. 2009) present general models for DSS performance estimation; (Garrido et al., 2016) focuses on a detailed radiation study omitting convection losses; (Gil et al., 2015) is oriented to CR optimization but does not include the optical evaluation of the dish; and (Beltran et al., 2012) and (Carrillo Caballero et al., 2017) also focus on the CR optimization but with simplified optical and thermal models. Due to the lack of specific experimental data of the CR performance, the validation of these models is based on the general electric performance of the DSS, on rough calculations of thermal losses or on unrealistic operating conditions. Consequently, the real performance of the DSS CR is not well-known yet.

To close this gap, this paper aims at improving the performance of the DSS CR by enhancing the reliability and relevance of the CR simulations and experiments. An experimental campaign was performed in order to collect detailed CR performance data with the goal of improving the simulation validation and increasing the available experimental data. The experiments consisted of a parametric experimental study of various DSS cavities changing the aperture diameter, the shape and the Stirling engine operating conditions. The main collected experimental data were the electric power and multiple temperature measurements along the CR. Then, a thermal simulation was validated against all the experimental measurements and used to find a higher-efficiency CR for laboratory conditions. Unlike other studies, the CR was designed to provide higher system electric outputs instead of higher CR thermal efficiencies. Moreover, the simulation was also utilized to calculate the thermal loss breakdown of the cavities experimentally tested. Additionally, the receiver tube temperature distribution is studied in order to be able to determine the real receiver operating temperatures on the front side (irradiated) from the measurements on the back (non-irradiated). Finally, as the operation control in DSS is usually made with thermocouples installed on a non-irradiated region, this study also led to the definition of a method to keep the peak receiver temperature constant from those thermocouple measurements. Thereby, desirable operating conditions can be set from viable temperature measurements to improve the receiver endurance.