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Scaling effects of a novel solar receiver for a micro gas-turbine based solar dish system

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ABSTRACT

Laboratory-scale component testing in dedicated high-flux solar simulators is a crucial step in the development and scale-up of concentrating solar power plants. Due to different radiative boundary conditions available in high-flux solar simulators and full-scale power plants the temperature and stress profiles inside the investigated receivers differ between these two testing platforms. The main objective of this work is to present a systematic scaling methodology for solar receivers to guarantee that experiments performed in the controlled environment of high-flux solar simulators yield representative results when compared to full-scale tests. In this work the effects of scaling a solar air receiver from the integration into the OMSoP full-scale micro gas-turbine based solar dish system to the KTH high-flux solar simulator are investigated. Therefore, Monte Carlo ray-tracing routines of the solar dish concentrator and the solar simulator are developed and validated against experimental characterization results. The thermo-mechanical analysis of the solar receiver is based around a coupled CFD/FEM-analysis linked with stochastic heat source calculations in combination with ray-tracing routines. A genetic multi-objective optimization is performed to identify suitable receiver configurations for testing in the solar simulator which yield representative results compared to full-scale tests. The scaling quality is evaluated using a set of performance and scaling indicators. Based on the results a suitable receiver configuration is selected for further investigation and experimental evaluation in the KTH high-flux solar simulator.

1. Introduction

Hybrid solar micro gas-turbines (MGTs) show potential to supply controllable power on demand to households in remote areas by using solar energy in combination with a back-up fuel (such as locally derived biodiesel). Additionally, the high exhaust temperature of the MGT opens up the possibility of supplying additional services, such as heating, cooling and water purification, through the use of poly-generation technologies (Aichmayer et al., 2014). Therefore, the EU-funded Optimised Microturbine Solar Power system project (OMSoP) was established aiming at demonstrating a 3–10 kW_{el} stand-alone hybrid MGT solar dish system. In a first phase a solar-only system has been installed at the ENEA Casaccia Research Center and commissioning tests have been successfully performed. So far, the tests have been conducted below nominal operation conditions.

In general, interest in using parabolic dish concentrators arises due to the potentially high concentration ratios and high optical efficiencies which allow to reach high receiver temperatures effectively (Pitz-Paal, 2008; Breeze, 2016). Solar dish concentrator installations of various sizes and shapes have demonstrated peak flux levels ranging from 1 to 12 MW/m^2 (Xiao et al., 2017; Schmitz et al., 2017; Reinalter et al., 2008; Ulmer et al., 2002; Lovegrove et al., 2011). Previous efforts on the power conversion unit for dish systems have mainly focused on the integration of Stirling engines (Mancini et al., 2003; Monne et al., 2013) as compared to this work where a MGT is integrated. Previous studies of volumetric air receivers for gas-turbine applications have focused on designs for tower-based systems (Avila-Marin, 2011; Buck et al., 2002; Romero et al., 2002; Kribuset et al., 2001; del Rio et al., 2015) which are not directly applicable for parabolic dish units. Furthermore, these receivers are typically designed for large-scale applications, with sizes ranging from 250 kW_{el} (European Commission, 2005) up to around 25 MW_{el} (Heide et al., 2012) as compared to the OMSoP MGT dish system with an electrical output in the range of 3–10 kW_{el}. For low power ranges (15–300 kW_{el}) Rosa do Nascimento et al. (2013) present a comprehensive summary on MGTs.

As the solar receiver needs to operate under high temperatures and high fluxes it is one of the key component in such concentrating solar power (CSP) systems. In earlier work (Aichmayer et al., 2015a) a new receiver concept was designed for the integration into a MGT solar dish with boundary conditions derived from the Eurodish concentrator

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Nomenclature

Abbreviations

CSP	concentrating solar power
DNI	direct normal irradiance
FP	focal point
HFSS	high flux solar simulator
MGT	micro gas-turbine
PDF	probability density function

Symbols

A	area [m^2]
a	absorption coefficient [1/m]
D	diameter [m]
E	irradiance (flux) [W/m^2]
h	specific enthalpy [J/kg]
i	light source spectral distribution [W/m^{2}nm]
K_{ext}	extinction coefficient [1/m]
L	length [m]
$\dot{M}$	mass flow [kg/s]
n	refractive index [–]
P	power [W]
p	pressure [Pa]
$\dot{q}$	surface heat source [W/m^2]
$\dot{q}_v$	volumetric heat source [W/m^3]
r	radial direction, radius [m]
R	reflection [m]
s	path length [m]
u	velocity [m/s]
T	temperature [K]
z	axial distance, axial direction [m]

Greek symbols

α	absorptivity [–]
δ	flux error [W/m^2]
ε	emissivity [–]
ε_p	porosity [–]
η	efficiency [–]
θ	zenith angle [rad]
Λ	wavelength discretization [nm]
ρ	reflectivity [–]
ρ	density [kg/m^3]
σ	stress [MPa]
σ_s	scattering coefficient [1/m]
τ	transmissivity [–]
φ	radiation absorption constant [–]
φ	azimuth angle [rad]
ϕ	cell diameter [m]
χ	random variable (0–1) [–]
ψ	exemplary variable

Subscripts

a	absorber
ap	aperture
b	beam
c	cavity
com	comparison
ct	center
el	electric
fp	focal plane
g	glass
i	incidence
in	inlet
m	measurement
max	maximum
min	minimum
n	nozzle
λ	spectral
o	other
out	outlet
p	passing
per	perpendicular
par	parallel
pt	point
rad	radiation
rec	receiver
ref	reference
RT	ray-tracing
t	transmitted
tot	total
v	volumetric
w	wall
I, II, III	principal direction indices

(Reinalter et al., 2008). In this work the concept is adapted to fit the specific OMSoP boundary conditions (Lanchi et al., 2015; Montecchi et al., 2017). The development process of solar receivers for CSP plants often involves the testing of a scaled version in a laboratory environment with controllable testing conditions and reduced system complexity as compared to the full-scale system. In recent years, high-flux solar simulators (HFSSs) have gained importance for the development of CSP components and systems as they offer a fully controllable and constantly available testing environment at lower costs than using a full-scale solar platform (Wang et al., 2013; Wang et al., 2017). A recent review of solar simulators (Gallo et al., 2017) showed that 26 HFSSs of various designs were in operation in late 2016 with 7 of them capable of providing a radiative power of more than 15 kW and 3 capable of providing more than 30 kW at the focal plane. In early 2017 another HFSS was completed offering radiative power of up to 310 kW (Wieghardt et al., 2017). With the vast majority of the operational HFSSs delivering a radiative power below 30 kW (Gallo et al., 2017) the main challenge of HFSS testing is caused by the fact that the radiative power delivered is lower than the power available at a full-scale CSP system. Additionally, differences of the peak flux and the spatial flux distribution can appear between HFSSs and full-scale systems. These differences result in different temperature and stress profiles within the solar receiver. The same issue arises for the evaluation of receivers in the scaling-up process of a CSP plant when building the actual system is impractical due to long lead times, too costly and/or impossible as the final design is not fully established and changes are anticipated. The need of laboratory tests and scaling is not only limited to solar dish systems but can also be found in tower based CSP plants. Even the most powerful HFSS in operation is not able to provide the full power needed for large utility-scale receivers with radiative power requirements in the order of 500 kW to several MW (Avila-Marin, 2011; Buck et al., 2002).

In light of the above, the main objective of this work is to determine a systematic scaling methodology for solar receivers and their radiative and power cycle boundary conditions to guarantee that experiments performed in the controlled environment of a HFSS yield representative results when compared to full-scale tests. To achieve this goal, the effects of scaling are investigated comparing the integration of a scaled solar receiver into the KTH HFSS and a full-scale receiver integrated