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Wind tunnel measurements of forced convective heat loss from multi-megawatt cavities of solar central receiver systems

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ABSTRACT

We investigated the forced convective heat loss from a model of a multi-megawatt cavity receiver of a concentrated solar power (CSP) tower system in a high-pressure wind tunnel. Measurements of 5 geometrical configurations of this model as well as measurement uncertainties are reported in this contribution. The experiment covered a Reynolds number range of between $2\cdot10^6$ and $8\cdot10^6$, based on the external dimensions and flow field. In general, the measured values are highly sensitive to the geometrical configuration, the wind velocity, and the wind direction. The results show that the maximum forced convective heat loss for all configurations occurs when the wind blows from frontal directions of between 60° and 80° relative to the tower symmetry plane. We found that the peak location does not vary for different inclinations, but does vary for different aperture openings. Also, the results show that the direction of the wind causes the forced convective heat loss to vary with a factor of up to 6.1, but at least with a factor of 2.6. Last but not least, our power-law correlation of the dependency of the forced convective heat loss on the Reynolds number matches literature values.

1. Introduction

Concentrated solar power (CSP) for the generation of electricity, or more general, concentrated solar thermal energy (CSTE) is one way of using the abundant and free solar energy. CSTE systems with a central tower are also known as solar central receiver (SCR) systems. In recent years, there has been a renewed interest in cavity receivers of SCR systems. As shown in the papers by Ho and Iverson (2014) and Ho (2017), this is due to the strive for higher temperature applications such as high temperature power cycles, particle receivers or thermochemical receiver-reactors.

During the operation of multi-megawatt (multi-MW) receivers of SCR systems, heat is lost mainly due to (a) the partial reflection of the incoming solar radiation on the receiver surface, (b) the radiation from the hot receiver surfaces to the surroundings, (c) the conduction to support structures, and (d) the mixed convection from the hot receiver surfaces to the surroundings.

Eyler (1979) and Clausing (1981) presented the basic mechanisms of natural convection in heated open cavities. They reported a division of the fluid in the cavity into a lower convective zone and an upper stagnant zone. In the stagnant zone the fluid is at similar temperatures and therefore the buoyancy forces are only weak and thus are the fluid movements. On the other hand, below the horizontal division, the temperature differences in the convective zone are large, causing strong buoyancy forces and thus strong fluid flow and mixing. Flesch et al. (2014) showed numerically that the position of this division is altered by letting wind blow with different speeds and directions. In Flesch et al. (2016) they validated their numerical model with cryogenic wind tunnel measurements (Flesch et al., 2015). In their experimental study, it was found that with different inclination angles, incident angles, and wind speeds the mixed convective heat loss changes significantly. All three studies apply to cavity receivers of about 2.4 m in diameter and mixed convection. Other experiments on natural or mixed convection include the work of Kraabel (1983), Clausing et al. (1987), Clausing et al. (1989) or Ma (1993). In all of these works, only simplified receiver models without a tower were tested. In addition, these models represent cavities no larger than approximately two meters in height.

McMordie (1984) measured the mixed convective heat loss from a cavity receiver on top of a 61 m tower. The absorber panel had a height of 3.5 m. He reported, amongst other points, an almost negligible influence of the wind speed and direction.

There has been a substantial amount of research on smaller scale cavities, such as those applied in dish concentrators. Examples of experimental work are the contributions by Taumoefolau et al. (2004) or

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Nomenclature

Acronyms

CSTE	concentrated solar thermal energy
CSP	concentrated solar power
CTA	constant temperature anemometry
SCR	solar central receiver

Latin symbols

A	area, m^2
B	constant
aperture ratio	$^{d_{ap}}/_{d_{cav}}$
C_{geo}	geometrical sensor constant, m^{-1}
d	diameter, m
E	voltage, V
g	standard gravity, 9.81 $m\,s^{-2}$
Gr	Grashof number, $^{g\beta(T_w-T_\infty)L^3}/_{\nu^2}$
h	heat transfer coefficient, $W\,m^{-2}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
l	length, m
L	characteristic length, m
m	exponent for Pr
n	exponent for Re
Nu	Nusselt number, $^{hL}/_{k}$
P	power, W
$\dot{Q}$	heat flow, W
r	radius, m
R	resistance, ohm
R^2	coefficient of determination
Re	Reynolds number, $^{\rho UL}/_{\mu}$
T	temperature, K
U	velocity, $m\,s^{-1}$

Greek symbols

α	wind incident angle, deg
β	coefficient of thermal expansion, K^{-1}
γ	cavity inclination angle, deg
Δ	difference of a quantity
μ	dynamic viscosity, $kg\,s^{-1}\,m^{-1}$
ν	kinematic viscosity, $m^2\,s^{-1}$
ρ	density, $kg\,m^{-3}$
σ	standard deviation
χ	absolute incident angle, deg
ω	sensor angle, deg

Subscripts

air	air
ap	aperture opening
calm	no wind
cav	cavity inside
conv	convection
el	electric
F	based on the friction velocity
film	film temperature
forc	forced
in	inner
i,aa	interpolated and area-averaged
max	maximum of all measurement points
out	outer
rel	relative
s	sensor
w	wall
wind	with wind
∞	bulk

Prakash et al. (2009). Examples of numerical work include the contributions by Paitoonsurikarn et al. (2004) or Xiao et al. (2012). These cavities are typically less than 1 m in diameter and therefore the results are not easily transferred to large scale SCR systems.

In recent years there were a few numerical and experimental studies on convective heat loss from cavities, for example the work by Flesch et al. (2016), Hughes et al. (2016), Shen et al. (2016), Hu et al. (2017), Lee et al. (2017) or Loni et al. (2017). Except the works of Hu et al. and Flesch et al., the studies were only applicable to smaller sized cavities.

In contrast to the mentioned works above, our work focuses on the pure forced convective heat loss from cavities mounted on a tower of an SCR system with a receiver thermal output power of around 100 MW. To measure on this scale is important, because as pointed out by Flesch et al. (2015) the available experimental data for large cavity receivers is limited. To measure the convective heat loss of such a receiver on multi-MW scale remains difficult to measure due to the complicated geometries and large dimensions. These large dimensions lead to Reynolds numbers Re of up to 10^7 and Grashof numbers Gr of up to 10^{14}. As a consequence, a physically similar model on a smaller length scale is hardly achievable if one would like to model the mixed convection and thus would need to keep both dimensionless numbers constant. In addition, there has been no publication, which is known to the authors, of pure forced convection in complex geometries like open cavities. Therefore, we chose to measure the forced convection in this experiment and hence, only the Reynolds similarity needs to be adhered to.

For the measurement of the forced convective heat loss we used wall-mounted hot-film sensors operated in constant temperature mode. Wall-mounted hot-film sensors have been used to measure local time-resolved heat transfer in several experiments, see the work of O'Donovan et al. (2011) for a thorough summary. Although the quantity of energy transferred from the sensors to the fluid within the cavity is low, it is important to make sure that the heated fluid is exchanged well enough with the surrounding fluid outside of the cavity. In other words, the bulk temperature in the cavity has to be equal to the free stream temperature. Otherwise, if the temperature in partially closed geometries is increased, the sensors would measure values corresponding to this higher, possibly unknown, bulk temperature. In our experiment, the sufficient exchange was checked with numerical simulations and theoretical estimations. Since conventional straight hot-film sensors are heavily dependent on the incident angle of the flow (Lomas, 1986; Tropea et al., 2007), we designed a ringlike wall-mounted hot-film sensor (Siegrist, 2016; Siegrist et al., 2017a) to reduce this angular dependency.

The preliminary results of this experiment were presented in the SolarPACES Conference 2017 (Siegrist et al., 2017b). Now, in the present work, we report the final results including the estimated measurement uncertainty. For the final results, we corrected and improved the post-processing. We also expanded our study with an analysis on the absolute incident angle. Further, we added an analysis on the Reynolds number dependency of the Nusselt number. And finally, we compare our results to literature on an externally heated cylinder.

With this work, we want to enhance the understanding of the influencing parameters of convective heat loss in heated open cavities. We want to achieve this by (i) analyzing large cavities ($d_{cav} > 10$ m) which are mounted on top of a tower, by (ii) comparing the results from three models with varied aperture and three models with varied inclination, and by (iii) focusing on the forced convection ($Gr/Re^2 \ll 1$).