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Research paper

On the influence of wind on cavity receivers for solar power towers: An experimental analysis

Robert Flesch [a,*], Hannes Stadler [a], Ralf Uhlig [b], Bernhard Hoffschmidt [c]

[a] Institute of Solar Research, German Aerospace Center, Karl-Heinz-Beckurts Straße 13, D-52428 Jülich, Germany
[b] Institute of Solar Research, German Aerospace Center, Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany
[c] Institute of Solar Research, German Aerospace Center, Linder Höhe, D-51147 Köln, Germany

HIGHLIGHTS

- Analysis of the influence of wind on cavity receivers.
- Usage of a similarity approach to scale the results to large receivers for solar power towers.
- Receivers with high inclination angles are more susceptible to wind.
- In some cases wind reduces the losses below the level of natural convection.
- Distribution of the heat losses on different sections gives insight in the heat loss mechanisms.

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ABSTRACT

The influence of wind on the convective losses of cavity receivers for solar power towers was analyzed experimentally in a cryogenic wind tunnel. At an ambient temperature of −173 °C a Grashof number of $Gr = 3.9 \cdot 10^{10}$ can be reached. Six different wind directions ranging from head-on to rearward flow, five wind speeds up to $Re = 5.2 \cdot 10^5$ and four inclination angles of the cavity in the range of $\phi = 0° \ldots 90°$ were analyzed. With a similarity approach the results can be transferred to a receiver in normal ambient conditions with an inner diameter of 2.4 m and a wall temperature of approximately 730 °C. The methodology and its restrictions are discussed in detail. The experiments show that the influence of wind on large horizontal receivers is small. However, with increasing inclination angle the receiver becomes more susceptible to wind, although the convective losses never exceed those of the horizontal cavity. In some cases a reduction of the convective losses under the level of natural convection was observed if wind is present. Additionally, local information about the heat losses of different heater sections are presented, which are used to analyze the heat loss mechanisms inside the cavity. A shrinking of the stagnant zone is found to be the main reason for the increasing losses.

1. Introduction

In solar thermal power plants solar radiation is concentrated with mirrors. The concentrated sunlight is used to produce heat. In contrast to other forms of energy heat can be stored easily. Therefore, the produced heat can be used directly to drive a conventional power plant or it can be stored first and used in periods when no sunlight is available. Thus, the technology is capable of producing dispatchable electricity.

Based on its concentrator solar power plants can be divided into three groups.

- parabolic trough and fresnel systems
- dish systems
- solar power towers.

The focus of the first system is a line in which the collector pipe is placed. In the two latter systems the sunlight is concentrated onto the so called receiver, a surface of small dimensions compared to the concentrator. Here, a cavity is one favorable design for the receiver, because radiative losses can be minimized. The cavity receiver consists of an enclosure which has an opening on one side – the so called aperture. The solar radiation enters the cavity through the

* Corresponding author.
E-mail address: robert.flesch@dlr.de (R. Flesch).

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Nomenclature

R	universal gas constant
$\mathrm{Gr} = \frac{\beta_{\mathrm{ref}}(T_{\mathrm{wall}}-T_{\infty})gL_{\mathrm{cav}}^{3}\rho_{\mathrm{ref}}^{2}}{\mu_{ref}^{2}}$	Grashof number
$\mathrm{Nu} = \alpha/k_{\mathrm{ref}} \cdot L_{\mathrm{cav}}$	Nusselt number
$\Pi_{\mathrm{T}} = \beta_{\mathrm{ref}} \cdot (T_{\mathrm{w}} - T_{\infty})$	dimensionless temperature spread
$\mathrm{Pr} = \frac{\mu_{\mathrm{ref}} c_{p_{\mathrm{ref}}}}{k_{\mathrm{ref}}}$	Prandtl number
$\mathrm{Re} = \rho_{\mathrm{ref}} L_{\mathrm{cav}} u_{\mathrm{wind}}/\mu_{\mathrm{ref}}$	Reynolds number
α	angle of wind direction
β_{ref}	volumetric thermal expansion
ϕ	inclination angle
ν_{ref}	kinematic viscosity at film temperature
k	conductivity
c_{pref}	heat capacity at film temperature
$\dot{Q}_{\mathrm{cond}}$	measured conductive losses
$\dot{Q}_{\mathrm{conv}}$	convective losses
$\dot{Q}_{\mathrm{rad}}$	calculated radiative losses
μ	dynamic viscosity
μ_{ref}	viscosity at film temperature
ρ	density field
ρ_{ref}	density at film temperature
$\mathbf{S}$	rate-of-shear tensor
$\tilde{d}_{\mathrm{i}}$	scaled inner diameter
$\tilde{T}_{\mathrm{wall}}$	model wall temperature
$\tilde{T}_{\infty}$	model ambient temperature
$\tilde{u}_{\mathrm{wind}}$	wind velocity in cryogenic wind tunnel
$\boldsymbol{g}$	acceleration of gravity
$\boldsymbol{u}$	velocity field
A_{tot}	total heated area inside the cavity
d_{i}	inner diameter of cavity
f_{R}	resistance ratio
h	enthalpy field
L_{cav}	length of the cavity
p	pressure field
P_{total}	measured electric power
T	temperature field
T_{ref}	film temperature
$T^{\star}$	dimensionless Temperature
T_{∞}	temperature of the environment
T_{wall}	temperature of the cavity receiver walls
u_{ref}	reference velocity
u_{wind}	wind velocity
k_{ref}	conductivity at film temperature

aperture and is absorbed by the enclosing walls. The walls either consist of tubes or they can be covered with a directly irradiated medium – e.g. particles. The cavities used for solar power towers and for dish systems are similar except in size. The typical inner length of a cavity for a solar power tower is larger than 1 m whereas the typical size of a cavity used for dish systems is less than 1 m.

As the temperature of the walls inside the cavity is higher than the temperature of the surrounding, part of the absorbed energy is lost due to radiation $\dot{Q}_{\mathrm{rad}}$, convection $\dot{Q}_{\mathrm{conv}}$ and conduction $\dot{Q}_{\mathrm{cond}}$ through the structure (Fig. 1). The conductive losses are small if an appropriate insulation is used and they can be calculated with adequate accuracy. The calculation of the radiative losses is a more complex phenomenon, but due to tools like ray tracing they can be simulated, too. Convection, however, is a highly nonlinear and

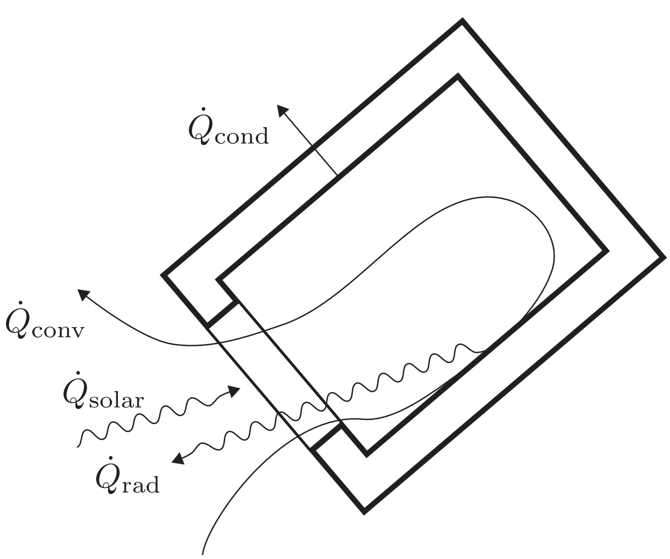

Fig. 1. The diagram shows the different heat loss mechanisms which reduce the usable share of the absorbed solar radiation $\dot{Q}_{\mathrm{solar}}$.

complex problem, especially when external effects like wind are taken into account. As it is crucial to have an estimate for the convective losses, several studies dealt with an analysis of the convective losses of cavity receivers. Since dish systems track the sunlight, the receiver moves. Therefore, its inclination angle defined as the angle between the normal of the aperture and the horizontal direction varies over the day. However, for cavity receivers of solar power towers this angle is fixed, but it is used as an optimization parameter in the design phase.

In case of natural convection the basic mechanisms have already been described by Eyler in 1979 [2] and Clausing in 1981 [1]. The hot air is trapped in the upper part of the cavity. The inner volume of the cavity can be divided into two zones as shown in Fig. 2 [1]. The upper part is the so-called stagnant zone. Here, the temperature is close to the wall temperature and the air is stably stratified. The lower part is the so-called convective zone. The cold air entering this zone through the aperture opening, is heated up and leaves the cavity through the upper part of the aperture. The boundary between the two zones can be approximated with the horizontal plane which goes through the upper lip of the aperture.

Kraabel [3] actually measured the losses caused by natural convection of a cubical cavity with an inner length of approximately 2 m. One side of the cube was missing. The others were heated electrically up to a maximum temperature of 815 °C. The heat transfer coefficient at the cavity walls was found to be independent of the length scale. This is an indication for a turbulent flow inside the cavity. The influence of the aperture position and size was investigated by Clausing et al. [4]. The experiments were performed in a cryogenic environment under similarity conditions to reach higher Grashof numbers for a small-scale model. Evidence of the stagnant zone in the upper part of the cavity was shown. Hess and Henze [5] performed experiments with a heated cavity inside a water tank. Due to the higher density of the water, higher Grashof numbers could be achieved. Dye flow visualization was used to analyze the flow pattern inside the cavity, including the transition to turbulence.