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Numerical analysis of the influence of inclination angle and wind on the heat losses of cavity receivers for solar thermal power towers

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Abstract

The convective heat losses of cavity receivers for solar thermal power towers are of great importance for the overall efficiency of the whole system. However, the influence of wind on these losses has not been studied sufficiently for large scale cavity receivers with different inclination angles. In this present study the impact of head-on and side-on wind on large cavity receivers with inclination angles in the range of 0° (horizontal cavity) to 90° (vertical cavity) is analyzed numerically. The simulation results are compared to data published in literature. When no wind is present the losses decrease considerably with increasing inclination angle of the receiver. In case of a horizontal receiver wind does not have a huge impact on the losses: they remain constant on a high level. In case of an inclined cavity wind increases the heat losses significantly in most of the cases, although the highest absolute value of the losses occurs for the horizontal receiver exposed to head on wind. In some cases, when wind is flowing parallel to the aperture plane, a reduction of the heat losses is observed. The temperature distribution in the cavity is analyzed in order to explain the impact of wind on the heat losses. Wind in general causes a shrinking of the zone with uniform high temperature in the upper region of the cavity, whereas wind flowing parallel to the aperture plane additionally inhibits hot air from leaving the cavity and therefore leads to an increased temperature in the lower zone.

Keywords: Concentrating solar power; Computational fluid dynamics; Open cavity receiver; Mixed convection; Wind

1. Introduction

Concentrating solar power (CSP) plants are a promising option for future energy production. Since the produced heat can be easily stored, these power plants are capable of providing demand-oriented electricity from a renewable source. Different CSP technologies exist: parabolic trough systems, solar power tower systems and dish/engine systems. In solar power towers a large number of mirrors, the so-called heliostats, reflect the sunlight onto a receiver on the top of a central tower (Romero et al., 2002). In the receiver, sunlight is absorbed and a fluid is heated, which can be used to produce electricity. In a dish system a single mirror tracks the sun and reflects it onto a receiver which is connected with the structure of the mirror.

Different designs for the receiver exist, one is the so-called cavity receiver. Here, the idea is to take benefit of the concept of a cavity in order to efficiently reduce the radiative losses. In technical designs radiative losses are eventually reduced to the same order of magnitude as the convective losses (McMordie, 1984; Kraabel, 1983). Thus,

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Nomenclature

Gr	Grashof number
Nu	Nusselt number
Re	Reynolds number
Ri	Richardson number
α	angle of the wind direction
$\bar{\beta}$	thermal expansion coefficient
$\bar{\lambda}$	conductivity at film temperature
$\bar{\nu}$	kinematic viscosity at film temperature
ΔT	temperature difference $T_{\mathrm{wall}} - T_{\infty}$
ν	local kinematic viscosity of the fluid
ϕ	inclination angle of the cavity receiver
ρ	local density of the fluid
τ_{wall}	wall shear stress
Θ	dimensionless temperature spread
λ	local conductivity of the fluid
$\bar{T}$	film temperature
A_{Cavity}	surface area of the inner cavity with the temperature T_{wall}
d	inner diameter of the cavity
d_{ap}	diameter of the receiver aperture
g	acceleration of gravity
L	inner length of the cavity receiver
T_{∞}	temperature of the environment
T_{wall}	temperature of the cavity receiver walls
u_{wind}	wind velocity

it is very important to estimate the convective losses of cavity receivers in order to calculate the overall efficiency of the plant. In general, convective heat losses cannot be easily calculated due to the complexity of buoyant flows. A common approach to calculate these losses is to use correlations, making them dependent on the particular design. Due to the importance of an estimation of the losses, several studies focused on the analysis of convective heat losses of cavity receivers. Some of these studies are presented in the following structured by their approach: theoretical studies, experimental studies and finally studies using computational fluid dynamics (CFD) simulations.

1.1. Theoretical and early numerical studies

In the first studies on convective losses it was proposed to calculate the losses with correlations for a flat plate of the size of the aperture (Wu and Wen, 1978) or for all walls inside the cavity (Tracey et al., 1977). Later on, Eyler (1979) performed an analysis of the flow inside a horizontal and an inclined cavity using a two-dimensional numerical code. The simulation results showed a stably-stratified region in the top of the cavity. Based on this upper zone inside the cavity Clausing (1981, 1983, 1987) developed a numerical model, which can be used to estimate the losses for any cavity geometry. The cavity is divided into two zones by the horizontal layer which goes through the upper lip of the aperture (Fig. 1). The fluid temperature in the upper zone, the so-called stagnant zone, is assumed to be equal to the wall temperature. For the walls in the lower zone, the so-called convective zone, standard correlations were used to calculate the heat flux from the walls into the convective zone. The layer between the zones is treated as wall as well. For the heat transfer through the aperture the velocity is calculated by assuming it is increasing linearly with the vertical height of the aperture. For a cavity exposed to wind this velocity is combined with the wind velocity to an effective velocity through the aperture. As the heat transport is limited by the ability to transfer energy from the walls to the convective zone, the temperature inside the convective zone is close to the ambient temperature. Since wind increases only the energy transfer across the aperture, Clausing concluded that it has almost no influence on the convective losses.

1.2. Experimental studies

Kraabel (1983) performed an experiment on convective heat losses using a cubical cavity with a Grashof number of $\mathrm{Gr} = 3 \cdot 10^{10}$. The cavity was mounted horizontally and only the losses caused by natural convection were analyzed. As the cavity was not placed inside a building, low wind velocity in front of the cavity could not be avoided,

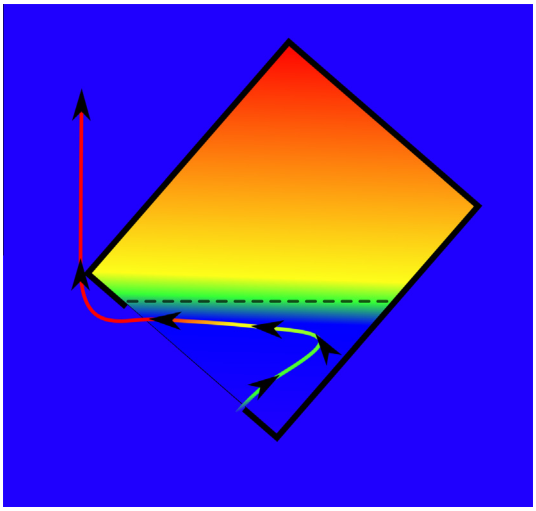

Fig. 1. Sketch of the temperature distribution inside of an inclined cavity. The cavity is divided by the horizontal layer (dashed line) which goes through the upper lip of the aperture. The upper zone is called stagnant zone and the lower zone is the convective zone.