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Computational fluid dynamics evaluation of the operating conditions for a volumetric receiver installed in a solar tower

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A B S T R A C T

A CFD (Computational Fluid Dynamics) model has been developed to study the wind influence and the effect of the return-air conditions on the efficiency of a volumetric receiver which was previously tested. The model validation obtained deviations lower than 5% for the air temperature at the absorber-cup outlet and an average deviation of 5.2% for the thermal efficiency evaluated in the receiver.

In order to determine the influence of the wind conditions, different velocity magnitudes and incidence angles have been studied. The results showed that the outlet air temperature decreases with increasing wind magnitude and, at a fixed velocity, the increase of the incidence angle produces the decrease of the air outlet temperature. In both cases, the outlet air temperature decreases according to a second-degree polynomial function.

Furthermore, the evaluation of the return-air influence considered its temperature and velocity as parameters. It was obtained that the greater the return-air temperature, the higher the air temperature at the outlet, and this temperature increases with lower return-air velocities.

It was also observed that the return-air influence is greater when the wind velocity decreases, thus new receiver designs should avoid the direct incidence of the wind and should also consider an optimisation of the return-air conditions.

1. Introduction

Solar thermal power plants have the potential to supply base-load electrical power. Therefore, CSP (Concentrating Solar Power) technologies have gained momentum in recent years, as the demand for clean energy sources continues to grow [1]. In order to accelerate the market penetration of CSP, it is important to improve the cost competitiveness with respect to other energy conversion technologies by increasing energy conversion efficiencies while maintaining or reducing cost. For that purpose, CSP should achieve high operating temperatures and heat-flux densities [2].

In particular, central receiver systems have undergone considerable development because they reach high concentration ratios and working temperatures. In solar power tower plants, the receiver, which accounts for about the 15% of the total plant investment cost, is an essential component [3] in which the concentrated solar energy is absorbed and then transferred to a working fluid. In order to improve the receiver effectiveness, different receiver concepts have been analysed in the last decades.

The volumetric-receiver concept consists of a highly porous material which absorbs solar radiation at different depth through its thickness, showing an effective area for solar absorption which is many times larger than that of thermal radiation losses. Furthermore, a fan sucks a working fluid (usually air) through the absorbent pores, and the convective flow captures the heat absorbed. The outlet fluid temperature should be higher than the temperature of the absorber material on its irradiated surface. These phenomena produce the so-called *volumetric effect* and results in a minimisation of absorber thermal radiation loss [4].

Atmospheric air as heat transfer fluid has advantages in terms of availability, cost and environmental impact compared to other commercial fluids [5]. Therefore, since the 1980s, different air volumetric-receiver designs were developed. One of them consisted of a ceramic foil receiver (SiSiC) covered by a matrix of square channels of quartz glass, which partly absorbs thermal radiation emitted by the ceramic part of the receiver. A one-channel model of this receiver obtained air outlet temperatures up to 1273 K and efficiency improvements up to 10% in comparison to a foil receiver without quartz glass structure [6].

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Nomenclature

A	area of the absorber cup, m^2
B	matrix of the momentum source term
B_2	inertial resistance factor dimensionless
C_μ	constant of the viscosity model dimensionless
c_p	specific heat capacity, J/kg-K
d	channel depth, m
D	matrix of the momentum source term
Dev	deviation, %
E	specific energy, J/kg
F	external body force, N
G	irradiance, W/m^2
g	gravitational acceleration, m/s^2
h	sensible enthalpy, J/kg
I	power, W
I_v	volumetric power, W/m^3
J	diffusion flux, kg/s-m^2
K_1	permeability coefficient, m^2
k	thermal conductivity, W/m-K
k_P	turbulence kinetic energy at the wall-adjacent cell P, m^2/s^2
l	channel width, m
m	mass flow, kg/s
N_{Chan}	number of channels in the absorber, dimensionless
p	static pressure, N/m^2
Q_{AR}	aspect ratio, dimensionless
Q_{EAS}	equiangle skew, dimensionless
Re	Reynolds number, dimensionless
S	source term
$sin(\theta)$	sine of the incidence angle, dimensionless
t	time, s
T	temperature, K
$tan(\theta)$	tangent of the incidence angle, dimensionless
V	volume, m^3
v	superficial velocity, m/s
x	position in axis x, m
y	position in axis y, m
y_P	distance from the centroid of the wall-adjacent cell to the wall P, m
z	position in axis z, m

Greek symbols

η	thermal efficiency, %
γ	porosity, dimensionless
θ	incidence angle, rad
μ	dynamic viscosity, kg/m s
ξ	optical extinction coefficient, m^{-1}
ρ	density, kg/m^3
τ	stress tensor, N/m^2

Subscripts

0	initial
1	absorber cup 1
2	absorber cup 2
3	absorber cup 3
4	absorber cup 4
av	average
conv	convective
eff	effective
f	focus
fl	fluid
h	heliostat
he	heat
i	ith
int	interval
ir	irradiated
j	species
m	mass
mag	magnitude
max	maximum
out	outlet
rec	receiver
ret	return
s	surface
so	solid
test	experimental

Haeger et al. performed the study of a wire mesh open solar volumetric air receiver, which obtained outlet air temperatures of around 1000 K [7]. This type of metal absorber was tested under pressurised conditions by Buck et al. Its demonstrated nominal conditions were 1073 K outlet air temperature and 15 bars [8].

Furthermore, ceramic absorbers were tested both under pressurised conditions, obtaining an outlet air temperature of 1473 K at 20 bars [9], and under atmospheric pressure (open receivers) [4]. The interest in ceramic volumetric receiver comes from the outlet air temperature reached. Wire mesh receivers are limited to mean outlet temperatures about 1073 K, whereas ceramic ones achieve higher temperatures and, as a consequence, the system efficiency increases. Furthermore, ceramic materials withstand higher flux densities and gradients, enabling a smaller receiver aperture, lowering systems costs, and minimising radiation losses. These features allow extending the absorber lifetime [4].

Previous studies of different solar receivers focused on the improvement of their thermal efficiency by new designs [10] [11], geometric and material properties [12] [13]. Furthermore, authors have also provided detailed models to study heat losses of receivers [14], local thermal non-equilibrium phenomena in porous-media absorbers [15], and the combined radiation-convection-conduction heat transfer including the Monte Carlo Ray-Trace method [16].

Nevertheless, the influence of the operating conditions on the receiver such as wind velocity and return-air conditions has not been analysed in detail, apart from the study of different air return modes developed by Marcos et al. for an open volumetric receiver [17]. This is an important issue to solve for the suitable operation of a solar tower.

Thus, this investigation analyses the influence of the wind and the effect of the return-air conditions on the efficiency of a HiTRec (high temperature receiver). This system is a ceramic open solar volumetric air receiver, which consists of a modular ceramic absorber, a supporting structure and an air-return system [4]. The study of the selected operating variables enables defining the proper strategy to operate the solar-tower facility, improving the thermal efficiency depending on the design of the volumetric receiver.

For that purpose, experimental data obtained from the test campaign performed at the PSA (Plataforma Solar de Almería) [4] were compared to the numerical results coming from a CFD