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Experimental and theoretical evaluation on the thermal performance of a windowed volumetric solar receiver

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A B S T R A C T

In the present work, we carried out an experimental analysis on the thermal performance of a windowed volumetric solar receiver (WVSR). A prototype was designed and tested in a dish concentrator system. Three silicon carbide (SiC) absorber slabs with different typical pore structures were tested. A unified theoretical model adequately considering the overall heat transfer processes for the WVSR is first put forward. The key component, a windowed cavity incorporated with the irradiated surface of the absorber was modeled in a coupled radiative-convection boundary condition, which detailedly concerning the porous surface structure of the absorber under local thermal non-equilibrium conditions. Model authentication was achieved by comparing the experimental and theoretical results. The maximum temperature of the outlet air was over 1003 K, and the best thermal efficiency (solar to thermal) obtained was 63.61%. The maximum deviations in the results were 9.4% and 2.3% for the temperature of the back wall and the outlet air, respectively. In terms of the thermal efficiency, the maximum deviation was 5.35%. These results demonstrate the feasibility of our model applied to describe the overall transport process from solar to thermal energy in a receiver.

1. Introduction

The concept of volumetric solar receiver (VSR) technology [1] has been proposed due to the feasibility of applying air as a working fluid in solar thermal power plants. This type of receiver consists of a porous medium that moves the irradiation from a surface into its volume in the direction of the thickness. Solar energy converts to thermodynamic energy in the working fluid. Compared with open-loop VSRs, higher solar shares and compressed air temperatures can be achieved for pressurized or windowed VSRs (WVSRs); these can be combined with modern gas turbine systems in recuperation or combined cycle mode to improve the conversion efficiencies of the solar heat by more than 50% [2].

Some typical VSRs have been designed and developed. However, Kribus pointed out that VSRs have an inherent limitation due to the decrease of the heat capacity located at the hot spot area; they suggested a pressurized loop to achieve a larger Blow number and uniformity of flow and temperature over the absorber [3]. Several types of receivers have been tested during the implementation of some research and development (R&D) projects. Pritzkow [4] designed the first pressure-loaded volumetric ceramic receiver (PLVCR); this updated type can supply outlet air temperatures as high as 1000 °C, with the pressure up to 10 bar. Furthermore, Karni et al. [5] proposed a frustum-like receiver characterized by a "porcupine" volumetric absorber. Ray-tracing calculations showed that the window reflection losses of the window were only about 1%. In addition, the test results showed that the pressure and temperature levels were greatly increased (30 bar and 1700 °C). Liu [6] conducted the first demonstration for a tower power plant (70 kW) in China. A solarized gas turbine system was developed to meet the design requirements; however, the potential for improving the thermal efficiency of the receiver is still great.

Solar hybrid power plants based on a combined cycle have significant potential for cost reduction. A receiver module consisting of a secondary concentrator and a volumetric receiver was tested in the REFOS project. Performance tests with this new secondary concentrator and a cold-water calorimeter demonstrated the expected increase in efficiency of about 10% (in the range of

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Nomenclature

c_p	Specific heat of fluid at constant pressure [J kg^{-1} K^{-1}]
d_p	Pore diameter [m]
E_b	Blackbody emissive power
F	Inertial coefficient
G	Incident radiation
h_v	Volumetric heat transfer coefficient [W m^{-2} K]
J	Radiosity
K	Permeability [m^2]
L_a	Thickness of an absorber [m]
$\dot{m}$	Mass flow rate [kg/s/m^2]
P	Pressure [Pa]
Pr	Prandtl number
q_0	Initial heat flux [W/m^{-2}]
q	Heat flux
$\hat{\boldsymbol{s}}$	Unit vector in the direction of fluid flow
T	Temperature [K]
u	Velocity[m/s]
$\boldsymbol{V}$	Velocity vector [m s^{-1}]

Greek symbols

α_{sf}	Specific surface area of the porous medium [m^{-1}]
ε	Emissivity
φ	Porosity
λ	Thermal conductivity [W m^{-1} K^{-1}]
μ	Dynamic viscosity [kg m^{-1} s^{-1}]
β	Extinction coefficient [m^{-1}]
σ	Stefan-Boltzmann constant
σ_s	Scattering coefficient
θ	Dimensionless temperature
ζ	Ratio of solid to fluid thermal conductivities
ρ	Density/reflectivity
τ	Optic thickness
ω	Single scattering albedo
Ψ	Dimensionless heat flux

Subscripts

a	Average/absorber
b	Back
c	Collimated/cavity
d	Diffuse
e	Effective/environment
f	Fluid phase
g	Glass
i	Inner/inlet
l	heat loss
o	outer
op	Optic
r	Radiative
s	Solid phase
t	Total
v	Void
w	Wall

70%) [7]. The system configuration, component efficiencies, and operation experiences in the first 100 h of the solar operation of the test was reported by Heller et al. [8]. The heat transfer characteristics of the silicon carbide (SiC) material affected by air velocity, porosity, pore diameter, and thickness of the porous medium absorber were theoretically analyzed by Bai et al. [9] and Xu et al. [10]. Roldán et al. [11] experimentally studied the heat transfer processes of a cavity solar furnace; the data were then compared with numerical simulation results. Moreover, 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 [12].

The effect of radiation in this high-temperature system needs to be taken into account along with the conduction and convection processes. Wang et al. [13] developed a detailed dimensionless local thermal non-equilibrium (LTNE) model using a Rosseland approximation for an air receiver. We then analyzed the transportation of radiative energy under collimated irradiation perpendicular to a packed bed [14]; in this way, the essential characteristic of the volumetric effect [15] in this process was revealed. Approaches for modeling the radiative transfer in the SiC material were compared by Kribus et al. [16], their results shows that the difference between the models are unapparent. An overview of the different approaches for the numerical modeling developed for the so called open-loop VSR, they suggested that a better representation of the radiative heat transfer should be introduced in future [17].

Since the window brings about some new heat transfer processes, including the radiation and cooling of the window itself, a novel model should be updated. However, from the literature review we find that little attention has been devoted to an overall analysis of WVSRs. In the present work, we carry out a small-scale prototype test on a WVSR; the test focuses on the analysis on the heat transfer characteristic of silicon carbide (SiC) foam ceramic material and the thermal performance of the receiver itself. We also propose a uniform model covering the main heat transfer behavior in the flow path of the heat transfer fluid (HTF), namely air. Boundary conditions are derived, taking into consideration the radiation between the window and the absorber based on the porous structure. The model validation is carried out through a comparison with the experimental results. In addition, the effects of inherent parameters of the porous medium, such as the interphase heat transfer coefficient (h_v) and emissivity (ε_s and ε_g for the absorber and the window, respectively), on the energy transport (incorporating thermal conduction, convection, and radiation) will also be examined systematically with respect to their effects on the heat transfer to and from the absorber.

2. Apparatus

The apparatus employed to study the thermal performance of the receiver is depicted schematically in Fig. 1. The high-temperature process coupled radiation, conduction, and convection will take place in the cavity due to the incident radiation supplied by the concentrator. The purpose of the experiment is to test the heat transfer characteristic of the SiC ceramic foam material and the thermal performance of the WVSR. This is then compared with the temperature field obtained from the numerical solution using our theatrical model.

2.1. Concentrator

The concentrator consists of a 16-mirror dish system with a reflectivity $\rho = 0.91$. The concentrator driven by a two-axis tracking system, which is illustrated in Fig. 1. The reflected radiation is located on the focal plane of the receiver, which is fixed on top of a support bracket. The mean geometric concentrating ratio is greater