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Research Paper

Study on heat transfer and stress characteristics of the pressurized volumetric receiver in solar power tower system

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HIGHLIGHTS

- An integration model coupling MCRT, FVM and FEM applied in PVR is developed.
- The coupled characteristics of optical-thermal-stress are numerically analyzed.
- Effects of flow rate and inlet temperature on receiver performances are discussed.

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ABSTRACT

In this paper, the analysis of heat transfer and stress characteristics in pressurized volumetric receiver (PVR) is presented by coupling Monte Carlo Ray Tracing (MCRT), Finite Volume Method (FVM) and Finite Element Method (FEM). Firstly, an integration model coupling MCRT, FVM and FEM applied in PVR is developed. Based on this model, the coupled characteristics of optical-thermal-stress are numerically studied. Meanwhile, the solar flux is homogenized using multi-point aiming strategy for multi-heliostat field zones. Finally, the effects of air mass flow and inlet temperature on the heat transfer and stress characteristics are discussed. The results indicate that the solar flux distributions on aperture and SiC porous absorber are more uniform using multi-point aiming strategy, and the peak flux in porous could be reduced by an order of magnitude compared with single-point. The peak stress of quartz window occurs at the contact position between the steel shell and quartz window, and the damage would not happen because of the peak stress is lower than the ultimate strength. The inlet parameters of air have significantly influences on the heat transfer and stress characteristics of receiver. For example, when the air with higher temperature is adopted, the SiC porous temperature increases by 20%, and the temperature and stress of quartz window increase by 31% and 60%, respectively. The overheating in SiC porous could occur using lower mass flow rates, however, the quartz glass stress exhibits a decreasing tendency when the mass flow decreases. Besides, the temperatures of outlet air and porous absorber increase when the flow rate decreases and inlet temperature increases which would lead to local overheating in absorber and lower stress on quartz window.

1. Introduction

Energy shortage is a very serious problem in the world and new energy resources are being developed positively by many countries [1,2]. Concentrating solar power technology is one of renewable energy technologies with board application prospect, which includes solar power tower system [3–12], solar dish system [13,14], parabolic trough system [15–17], and linear Fresnel system [18,19]. And many solar tower power plants have been built in the world during these years. The receiver is one of the key components in the tower plants, in which the pressurized volumetric receiver (PVR) has been widely adopted [20]. With increasing solar flux and temperature in the PVR, the risk of local overheating and structure failure become a big challenge [21,22] which would strongly influence the receiver security. For example, the SiC foam ceramics has been widely used as the porous absorber in PVR, and its melting temperature is 1673 K [23]. In operation, higher solar flux

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Nomenclature

c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
C_2	inertial resistance coefficient of porous
D_{por}	mean pore size of porous (mm)
E	elasticity modulus (MPa)
$\bar{f}$	mean friction coefficient
h_o	convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
m_s	mass flow rate of air ($kg\,s^{-1}$)
$\overline{Nu}$	mean Nusselt number
q	heat flux ($MW\,m^{-2}$)
ΔT	temperature difference (K)
T	node temperature of solid region for FEM (K)
T_{in}	inlet temperature of air (K)
T_{init}	node initial temperature of solid region for FEM (K)
T_{max}	maximum temperature (K)
T_{melt}	melting temperature (K)
T_{out}	outlet temperature of air (K)

Abbreviations

FVM	Finite Volume Method
FEM	Finite Element Method
MCRT	Monte Carlo Ray Tracing
PVR	Pressurized volumetric receiver
R1	Receiver 1#

Greek symbols

α	linear thermal expansion coefficient (K^{-1})
α_{por}	permeability of porous
δ	deformation (m)
ε_{por}	porosity of porous
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity (Pa s)
ν	Poisson's ratio
σ_1	tensile stress (MPa)
σ_b	tensile strength (MPa)

Superscripts

f	fluid
i	inner surface
in	inlet
init	initial
melt	melting
max	maximum
out	outlet
o	outer surface
por	porous

would lead the temperature of SiC porous absorber increases sharply, thus the overheat-burnout in SiC porous happens when the temperature exceeds 1673 K. Besides, the crystallization-chipping-degradation would also exist in the quartz glass window if its temperature exceeds the limiting temperature of 1073 K [21]. Furthermore, due to the different thermal expansions between stainless steel shell and quartz window, the quartz window where is jointed to the steel tubular would be damaged by higher stress, thus the airtightness of PVR is threatened.

Lots of researches on the solar flux distribution in tower receiver have been carried out using the experimental and numerical methods. The results of literatures [24–31] showed that the solar flux distribution on the receiver surface or inside the absorber is extremely non-uniformed. Besides, several researchers [32–35] have also discussed the characteristics of solar flux distribution in PVR with different geometric and structural parameters of heliostats and receivers using the method coupling Monte Carlo Ray Tracing (MCRT) and Finite Volume Method (FVM). Especially, based on the PVR in REFOS project and the heliostat field in DAHAN tower plant, He and Cui et al. [35] established the solar radiation transmission and absorption model from the heliostat field to PVR, and the performances of solar flux distribution were investigated by MCRT method. Besides, in order to avoid failure in receiver induced by the non-uniformed solar flux distribution, several mitigation measurements have also been proposed. For example, Besarati et al. [36] developed a new optimization algorithm by which the peak solar flux on the receiver surface has been reduced effectively. In order to optimize the temperature distribution within a PVR at the PSA plant, a method of a heuristic knowledge-based heliostat control strategy with five aiming points has been proposed by García-Martín et al. [37]. Yu et al. [38] proposed a model with multi-point in the cavity receiver and the solar flux distribution on receiver surface was optimized. Alberto et al. [39] analyzed the solar flux characteristics on the cylinder receiver surface using the multi-focus points method, the results exhibited that the uniformity of solar flux distribution was improved. Furthermore, in order to improve the thermal efficiency and operation stability of receiver, extensive researches on developing and improving the receiver structure types have also been carried out [21,40–46].

However, it is found that few papers have simultaneously focused on the research of solar radiation energy, heat transfer and stress characteristics in the PVR until now. In this paper, an integration model coupling MCRT, FVM and FEM applied in PVR is established. Based on this model, the coupled characteristics of optical-thermal-stress are numerically analyzed. Meanwhile, the solar flux is homogenized using a multi-point aiming strategy with multi-heliostat field zones. Finally, the effects of air mass flow and inlet temperature on the heat transfer and stress performances are discussed.

2. Model description

2.1. Physical model

The north-south staggered heliostat field of DAHAN solar tower power plant [47] and the pressurized volumetric receiver (PVR) of PSA REFOS project [22,26] have been adopted. The PVR consists of SiC porous absorber, quartz glass window, stainless steel tubular and secondary concentrator. Fig. 1 shows the corresponding structure diagram. In the PVR, the acceptance angle of secondary concentrator is 20°, the aperture diameter is 1200 mm and the length is 1000 mm. For the

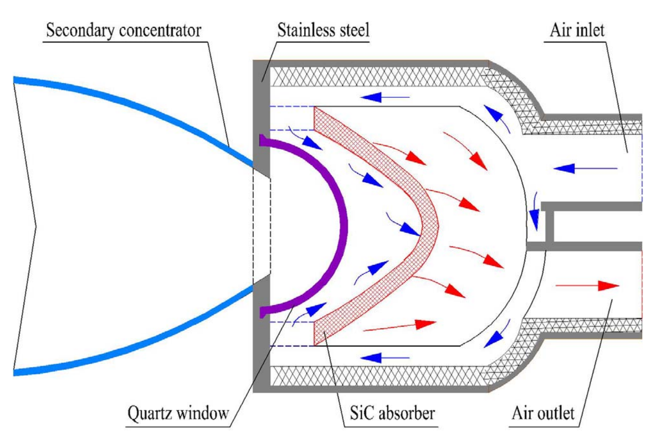

Fig. 1. The PVR structure diagram of REFOS type.