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Coupled heat transfer performance of a high temperature cup shaped porous absorber

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ABSTRACT

In this article, a newly designed volumetric solar receiver (VSR) using cup-shaped Al_2O_3 porous absorber is studied through numerical simulations and experimental verification. The absorber achieves several advantages including lower heat loss and higher uniformity of heat flux. The ray tracing method is adopted to obtain the external radiation source. The inner radiative exchange within the cavity is solved with the aid of User Defined Function (UDF). The heat transfer performance has been compared based on different parameters including window reflectivity, porosity and mass flow rate. The theoretical advantages of using cup-shaped Al_2O_3 absorber are presented. The experimental verification is adopted based on sixteen-dish concentrator (SDC) platform.

1. Introduction

Solar thermal power, usually collected by the concentrating solar collectors, possesses great potentialities serving for the thermal power plants or heat engines. Currently high temperature VSR is developed by only a few groups in the world and still facing industrial barriers. Due to its simpler design and commercial prospects, high temperature VSR has become a promising method of capturing solar rays for large scale systems [1].

Porous solid is the medium containing voids which are typically filled with liquid or gas. It provides high surface area, disturbed flow conditions and enhanced heat transfer. It also helps to decrease the temperature difference between the solid and fluid, which could therefore reduce the radiation loss and prevent local overheating [2]. The research on the thermal behavior of single porous layer has been covered thoroughly. Becker et al. had investigated the flow stability and heat transfer performance of porous materials theoretically and numerically [3]. One dimensional physical model had been analyzed in order to obtain the relationship between air flow resistance and outlet temperature [4]. Xu et al. [5] has presented the numerical investigation on porous media heat transfer in a solar tower receiver. Several effects such as the geometric and operating parameters of porous component had been investigated using local thermal non-equilibrium (LTNE) model [6]. The coupled heat transfer problem inside the VSR was solved by using LTNE with P1 approximation [6,7]. It can be also solved with the aid of Rosseland approximation [8]. In addition, the Monte Carlo Ray Tracing (MCRT) method and Finite Volume Method coupling method had been developed to investigate the heat transfer characteristics of porous absorber [8,9]. The MCRT was adopted to simulate the transport of solar radiation [10]. Most of the studies before focused on the heat transfer between fluid and solid region. The performance of porous absorber assembled in a practical VSR is seldom discussed.

The porous materials were normally processed as a single piece of layer for the VSR [11]. The incoming fluid was also considered as parallel to the porous layer [8]. For the practical applications, instead, the inlet gas may be located at side surface [10,12]. The porous structure can seriously influence the thermal heat transfer [13], which should be specially designed. The majority of previous research has mainly focused on the characteristics along the ray axis of concentrator [4,8]. The heat transfer performance for practical 3-D structure needs to be investigated further. On the other hand, the proportion of inner radiative exchange in a VSR tends to be much larger at higher temperature, which was seldom considered. The entrance window was simplified as perfectly transparent, which in fact involves complex transmission and reflection process.

In this article, the heat transfer performance of a self-designed VSR is studied. The VSR uses a cup-shaped Al_2O_3 ceramic foams as the absorber, which ensures low temperature at side surface

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Nomenclature

VSR	volumetric solar receiver	UDFs	user-defined functions
SDC	sixteen-dish concentrator	ρ	density (kg/m^3)
ECR	energy concentration ratio	T	temperature (K)
ϕ	porosity	C_p	specific heat capacity (J/(kg K))
d_p	average particle diameter of porous material (m)	V	viscosity of fluid (m/s)
λ	heat conductivity (W/(m^2 K))	μ_f	dynamic viscosity of fluid (N s/m^2)
h_v	volumetric convection heat transfer coefficient (W/(m^3 K))	n	refractive index
h	enthalpy (J/kg)	q_r	external heat flux source (W/m^2)
Pr	Prandtl number	$\dot{m}$	mass flow rate (kg/s)
Re	Reynolds number	κ_e	extinction coefficient
σ	Stefan–Boltzmann constant	κ_α	absorption coefficient
ε	emissivity	κ_s	scattering coefficient
$\delta_{k,i}$	Kronecker's delta function	φ	radiation view factor
LTNE	local thermal non-equilibrium	G_k	surface irradiation (W/m^2)
		J	surface radiosity (W/m^2)

and decrease heat loss by the shell. The inner cup surfaces can provide smaller view factor for radiation loss by the window. The radiative exchange inside can decrease the maximum temperature of solid region to avoid overheating. The concentrated solar heat flux on the porous absorber was simulated by ray tracing method. The net distribution can be then substituted into the energy balance equation for calculating the equations of inner radiative exchange, including diffuse reflections and emissions between high temperature porous surfaces and quartz window. The thermal heat transfer and pressure drop of the porous receiver is studied using FLUENT software with UDF. In addition, the experimental verifications have been adopted based on the SDC platform.

2. The VSR for modelling and testing

A typical VSR consists of the glass window, radiation absorbing materials and insulation shell. After being transmitted through the optical window, the sunlight is concentrated onto the absorption surface, and the radiative heat transfer happens within the receiving materials, for which the structures of honeycomb [14], fiber mesh [15] or ceramic foams [16,17] are usually selected. The advantage of porous materials lies into the large specific surface areas which can improve the heat transfer efficiency obviously [18]. A VSR normally adopts porous metal or ceramic materials as the absorber. Porous metal is readily oxidizable at around 800 °C hence the availability is limited. Porous ceramics has become the most appropriate materials for high temperature working conditions. The limiting temperatures of SiSiC and SiC reach up to 1200 °C and 1500 °C, respectively. The maximum temperature of our VSR is close to this limit, which will be proved in the following study. The alumina ceramics (Al_2O_3), by contrast, has a higher melting point of 2000 °C [1] and remains stable working condition especially using air as the heat transfer fluid, and is able to meet the demand of high temperature resistance.

The Al_2O_3 ceramic foams are processed into a cup-shaped absorber as is shown in Fig. 1. The inner cup surfaces provide smaller view factor for radiation loss by the window. The radiative exchange inside can obviously decrease the maximum temperature of solid region to avoid overheating. A flat half-elliptic shaped piece of glass is the best structure to cope with the extremely high pressure compared with the other shape. The edge of this window was produced as a flat area for the sealing purposes. The insulation shell was constructed by two concentric steel sleeve, to create a hollow space for the air flow and heat insulation. The air inlet was arranged along the side of VSR, passing through the surrounding cavity which ensures a good heat insulation effect. Then the air will firstly pass through the side porous absorber to be preheated and decrease the heat loss from the side surface further. After that, it will go through the central absorber and participate in the high temperature heat transfer.

The assembled VSR for testing is presented in Fig. 2. There are four pairs of cylindrical holes distributed on the concentric sleeve as a cross. One single inlet at the outer sleeve corresponds three outlets at the inner sleeve, with the diameter of 14 mm. The alumina porous absorber was designed as a cup-shaped structure, with the central absorber at 50 mm radius, side absorber at 60 mm length and 15 mm thickness. The porosity and pores per lineal inch (PPI) of the porous alumina component were selected as 80% and 25%, respectively. Due to its fragile nature, the ceramic foam were cut by hand. The entrance size of the quartz window was machined to fit with the cavity. The semi-major and semi-minor axes of the ellipsoidal window are 50 mm and 30 mm, respectively. The thickness had been determined as 8 mm under the conditions of 5 bars and concentrated heat flux. A thermocouple is adopted at the outlet of VSR to measure the real-time temperature of heated air. The heat transfer performance of the current VSR has been tested based on the SDC in Harbin Institute of Technology [19]. The SDC consists of sixteen facets on the girder grillage in two circles. Each small facet having a diameter of 1 m is made of a paraboloid reflector with the focal length of 3.25 m. The optical reflectivity is considered as 0.94.

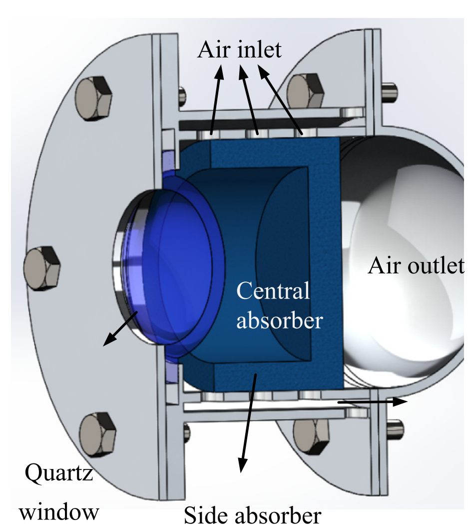

Fig. 1. Structural model of the VSR with cup-shaped Al_2O_3 porous absorber.