Types of High-Temperature Fixed-Bed Particle Solar Receivers

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Among a large number of receivers, the fixed-bed Particle Solar Receiver (PSR) represents a new pathway to high temperature with maximum overall thermal efficiency. The incoming solar radiation can penetrate deeper into the fixed-bed PSR filled with semi-transparent quartz and ceramic particles (spheres or Raschig rings), resulting in an increased volumetric effect. The semi-transparent PSR is full of the quartz glass spheres and/or quartz glass Raschig rings with smooth surfaces for high-temperature applications. The opaque PSR utilizes the ceramic material (e.g., silicon carbide, zirconium oxide and aluminium oxide) or a high-temperature alloy as heating particles. The mixed PSR is defined as a PSR that is full of mixed particles with various optical performances, namely, some quartz glass particles and other opaque particles.

Keywords: solar energy ; Particle Solar Receiver

1. Introduction

The growing problems of CO_2 emissions and concerns about energy security have strengthened interest in alternative non-oil energy sources. Solar energy is regarded as one of the most promising renewable energies because of its abundance and wide applications in nature [1]. However, although solar radiation is a high-quality energy resource due to the high temperature of its source, the low flux density limits its industrial applications. Concentrated solar power (CSP) that concentrates the incoming solar radiation to a high flux density level by the mirrors is an important candidate for becoming a major clean, renewable energy resource in the future. In the framework of the CSP, the incoming solar radiation is concentrated, and simultaneously delivered to the solar receivers [2].

The solar receiver is one the most important components in high-temperature solar thermal applications, which can make use of the incoming solar radiation as high-temperature processed heat. With the help of the high operating temperature, the solar receiver can increase the solar thermochemical reaction rate and the solar thermodynamic efficiency [3]. However, high-temperature receivers also face several challenges, including the development of geometric configurations to minimize heat loss, absorber materials and HTF to own high reliability at high temperatures over repeated cycles [4]. To a certain extent, it is very important and urgent to improve energy efficiency to alleviate current energy and environmental challenges.

Among various high-temperature solar receivers, particle solar receivers (PSRs) are currently being designed and developed as a means to achieve higher operating temperatures [5]. Unlike the traditional heat transfer fluid, solid particles have several advantages, including a wide operating temperature range, direct usage as a thermal energy storage medium, stable chemical properties, safety under high temperature and so on. These characteristics enable a PSR to achieve high-temperature applications exceeding 1000 °C and can drive efficient cycles [6].

The PSR uses solid particles to absorb incoming solar radiations either directly or indirectly [7]. The direct PSR irradiates solid particles directly when they pass through the receiver aperture, while the indirect PSR irradiates the tubes or other enclosures first, and then transfers heat to the solid particles. In addition, the solid particles may also be mobile (fluidized-bed) or static (fixed-bed). For mobile solid particles, the driving power includes gravity force, centrifugal force, buoyant force, conveyer belt and so on. For the fixed bed, the solid particles maintain static during the heating process. Once heated, solid particles can be stored in the receiver or delivered to an isolated reservoir and used to heat a secondary working fluid.

Compared with the mobile particles, the fixed-bed PSRs filled with static particles have attracted increasing attention due to their several advantages: high specific surface area, chemical stability, thermal energy density and cost effectiveness [8]. The fixed-bed PSRs have been extensively used as a medium for sensible and latent thermal energy storage and as a reacting medium in thermal chemical reactors [9][10]. However, the fixed-bed PSR has not been explored as a solar receiver for its inherent drawbacks, including low porosity and poor radiation penetration [11]. Recent studies show that these issues would be addressed by using semi-transparent glass particles as the heating medium. The semi-transparent glass particles with various shapes can considerably improve the radiative and convective heat transfer performances [12]. This type of solar receiver represents one potential way to realize a high operation temperature (>1000 K) with high efficiency.

When the solid particles absorb the incoming solar radiation to reach the high temperature, the absorbed heat is subsequently transferred to the working fluid through the convective heat transfer and the other particles via the radiative heat transfer, as well as the contact heat transfer. Among the process of the whole heat transfer within the receivers, the radiative heat transfer is fundamental to the thermal performance of the fixed-bed PSRs [13]. On the one hand, the thermal process of the PSR is derived by incoming solar radiation, and the thermal performances (e.g., maximum operating temperature, thermal efficiency) are determined by the absorption performances (or penetration depth) of the irradiation inside the PSRs. On the other hand, an obvious temperature gradient would appear inside the receiver domain due to the extremely non-uniform incoming solar flux distributions. The radiative heat transfer dominates the heat flux between the solid particles due to the high temperature level and the low contact heat transfer coefficient.

Furthermore, unlike the convective heat transfer and heat conduction, the radiative heat transfer is specified by volumetric characteristics, which means that, in theory, any solid particle can exchange radiation energy between the other particles over the whole volume [14]. In view of the polymorphic fixed-bed with different particle shapes and materials, the radiative heat transfer process that occurs inside the fixed-bed PSRs would be dramatically complex. So, the governing equation and the algorithm of the radiative heat transfer inside the fixed-bed PSRs should be processed carefully to retain accuracy and stability. Moreover, the key to improving thermal performance needs to be fully indicated to promote the development of solar thermal applications.

2. Types of High-Temperature Fixed-Bed PSRs

Increasing the penetration depth of the incoming solar radiation can potentially result in a higher outlet temperature and thermal efficiency [15]. This phenomenon is well known as the volumetric effect. Although the thermal radiation (e.g., incident solar radiation, re-radiation emitted from the solar particles) can penetrate into the fixed bed with a large number of pores, the penetration depth is quite small because of the low porosity and the tortuous passageway. Thermal efficiency can be increased by increasing the solar absorptance and/or decreasing the thermal emittance [16]. However, this method is very expensive when all of the particles are deposited with spectrum-selected coating.

Another promising method to produce the volumetric effect is adopting semi-transparent particle materials, such as quartz glass spheres, quartz glass Raschig rings (a short hollow cylinder with equivalent height and outer diameter) and so on [17][18]. In practice, particles make up the major portion of the fixed-bed PSR. Herein, the radiation properties (extinction coefficient, albedo and scattering phase function) of the fixed-bed PSRs are significantly dependent on the transmission property of the particle materials. According to the transmission property of the particle materials, the fixed-bed PSRs could be classified into three types, including semi-transparent PSRs, opaque PSRs and mixed PSRs.

2.1. Semi-transparent PSRs

The semi-transparent PSR is full of the quartz glass spheres and/or quartz glass Raschig rings with smooth surfaces for high-temperature applications. The quartz glass is the preferred particle material due to its several advantages, including spectrum-selected properties, good thermostability and superior abrasion resistance. This is especially true for the spectrum-selected properties, which have a low absorption coefficient for the solar radiation while having a high absorption coefficient for the infrared re-radiation. It is key to enforce the volumetric effect and improve thermal efficiency [19][20].

When the solar radiation strikes at the semi-transparent PSR, it may be encountered by either the pore channels or the quartz glass particles. For the former, the solar radiation can penetrate directly inside the pore channels until it touches the particles. For the latter, a part of the radiation is reflected back to the pore channels; the other part is refracted into the particle bodies. The proportion of these two parts is determined by reflectance, which is calculated by the incident angle measured between the local normal direction and the incident direction through Snell’s law. Minor solar radiation would be absorbed by the particle materials when it enters the particle bodies for the low absorption coefficient. Major solar radiation would be able to reach the opposite side and be refracted out from the particle bodies, and then enter the pore channels again until meeting other particles [21]. So, repeatedly, the incoming solar radiation can penetrate deeply into the semi-transparent PSR.

Generally, the effective extinction coefficient of the semi-transparent PSR is mainly determined by the absorption coefficient of the quartz glass materials associated with the reflectance of the radiation beam, which is about several per meter (m^{-1}) magnitude for the incoming solar radiation, roughly [22].

2.2. Opaque PSRs

The opaque PSR utilizes the ceramic material (e.g., silicon carbide, zirconium oxide and aluminium oxide) or a high-temperature alloy as heating particles. These materials are opaque to any thermal radiation despite their favorable properties at high temperatures, and are widely used as porous absorbers [23][24]. When the incoming solar radiation reaches the opaque PSR, most of it is absorbed by the particles at the inlet wall, and a minimum amount can penetrate into the receiver through the pore channel. In this case, the peak temperature will appear at the inlet wall, resulting in a large amount of thermal radiation loss emitted from the receivers. In accordance with the porous ceramics, the extinction coefficient of the opaque particle fixed-bed would be up to hundreds per meter [25].

Multi-layer designs have been proven to be helpful to ameliorate this situation, and are widely applied to the porous volumetric receiver [15][26]. Inside each layer, the porous absorbers with given parameters (i.e., porosity, pore sizes, geometric configurations and spectral properties) produce particular performances, such as a volumetric heat transfer coefficient and extinction coefficient. For the entire multi-layer receiver, stepwise performances may be realized to enhance the volumetric effect [27][28]. Similarly, the opaque PSR would be divided into several sections along the radius direction and/or the asymmetry axis, and each section would be filled with different particles (configurations, materials and sizes) to improve thermal efficiency.

2.3. Mixed PSRs

In this work, the mixed PSR is defined as a PSR that is full of mixed particles with various optical performances, namely, some quartz glass particles and other opaque particles. In the mixed PSR, the proportion of the opaque particles should be increased gradually along the penetration direction of the incoming solar radiation. Consequently, the axial average extinction coefficient of the mixed PSR would be increased sharply since the extinction coefficient of the opaque particle is almost two orders of magnitude larger than that of the quartz glass particle.

According to Beer’s law, the source term of the incoming solar radiation decreases exponentially with the product of the extinction coefficient and the penetration depth, approximatively [4]. If the growth of the axial average extinction coefficient of the mixed PSR is designed particularly, the source term of the incoming solar radiation would be increased smoothly along the penetrating direction. In theory, the HTF can be heated gradually with an increased source term level when it passes through the mixed PSRs. As a result, a significant volumetric effect would be demonstrated in the mixed PSRs.

For the semi-transparent and opaque PSRs, the source term of the incoming solar radiation decreases with increasing penetration depth. Additionally, the decreasing speed of the source term curve in the opaque PSR is much faster than that in the semi-transparent PSR with a smaller extinction coefficient. These situations result in the front wall temperature being higher than the outlet HTF temperature. The volumetric effects produced by these two types of PSRs are rather poor. However, the source term curve within the mixed PSR may increase with increasing penetration depth, leading to a lower front wall temperature. In a nutshell, the mixed PSR with a particular design is more appropriate for the heat transfer process in pursuit of a higher working temperature and thermal efficiency.

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