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Innovative design of a solar volumetric receiver: Arrangements of absorbing block configurations

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ABSTRACT

Innovative design of a solar volumetric receiver is introduced and influence of the absorption coefficient and geometric orientations of the absorbing blocks on the receiver performance is presented. An analytical expression is incorporated for the selection of the absorption coefficient of the absorbing blocks within the receiver; in which case, the intensity parameter (n) is used to alter the absorption characteristics of the blocks. The aerodynamic design of the absorbing blocks is considered to minimize the pressure drop across the receiver inlet and exit ports. Air is used as the working fluid inside the receiver. Energy transfer parameter is defined to assess the energy gain by the working fluid against the amount of solar energy absorbed by the blocks. Similarly, the global effectiveness of the receiver is introduced to determine the ratio of the useful thermal energy gained by the working fluid over the overall solar irradiation reached to the receiver. It is found that the energy transfer parameter increases for certain arrangements of the absorbing blocks in the receiver; in which case, power intensity parameter is $n = 0.35$ and two absorbing blocks configuration results in the highest energy transfer parameter. The similar arguments are true for the global effectiveness of the solar volumetric receiver.

1. Introduction

Efficient energy harvesting from solar radiation is one of current changes in renewable energy research. Increasing absorbed solar energy while reducing the device size is the critical requirement for the solar energy harvesting. A solar volumetric absorption provides a control of solar energy absorption per unit volume and increases the device performance as compared to those operating with the selective surfaces (Yilbas and Kaleem, 2015). In general, two important parameters need to be considered carefully in the solar volumetric absorption systems. The first parameter involves with the proper selection of the working fluid in the volumetric receiver in terms of enhanced solar absorption characteristics, low fluid viscosity for reduced pump power, high specific heat for large storage of thermal energy within small temperature rise, high density to increase mass flowrate at low flow velocities, and high latent heat of melting/evaporation if phase change is considered. The second parameter is related to the geometric configuration of the solar volumetric receiver; in which case, the working fluid do not suffer from high pressure increase due to drag, the shadow effect should be minimized for the working fluid while allowing high rate of solar power absorbed by the working fluid in the system, and maximizing thermal contact area between the working fluid and the active structure of the absorber surfaces in the receiver. In addition, the cost effective design and manufacturing as well as operational stability of the system with low maintenance cost are the primary concerns for the utilization of the solar volumetric receivers. To increase the mass ratio of the working fluid over the structure in the solar receiver, the design configuration of the solar volumetric receiver needs to be optimized. Although the experimental study of such design provides useful information on the system performance over the design parameters, the numerical simulation of such system also provides similar details within short duration and cost effective manner. Consequently, investigation of the solar volumetric receiver performance incorporating the innovative design configuration via numerical analysis becomes necessary.

Considerable research studies were carried out to examine the performance of the solar volumetric receivers. The performance of a volumetric solar absorption in a channel with presence of phase change material in a carrier fluid was studied by Siddiqui et al. (2016). They showed that the performance parameter improved considerably for the absorbing plate location at the channel bottom. However, the pump power loss parameter became the highest for the absorber plate location at the mid-height of the

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channel. High temperature volumetric solar absorber incorporating the ceramic absorbers was investigated by Mey-Cloutier et al. (2016). They demonstrated that the use of small pore diameters with low porosity of ceramics resulted in the improved absorber efficiency. In addition, the use of selective materials was found to be promising for atmospheric air receiver, provided that the solar absorptivity and the durability could be controllable. The analysis on the unified heating model for a pressurized volumetric solar receiver was carried out by Wang et al. (2016). They introduced the key design parameters in the analysis, such as those related to the pores structure, the volumetric heat transfer coefficient, and the emissivity of the window. Graphene nanoplatelets-nanofluid-based volumetric solar collector for domestic hot water systems was examined by Vakili et al. (2016). They indicated that the collector efficiency increased by increasing the nanofluid weight fraction and the maximum collector efficiency was obtained at 0.015 kg flow rate for both the base fluid and the nanofluids. The harvesting of solar thermal energy via nanofluid-based volumetric absorption systems was studied by Khullar et al. (2014). Their findings revealed that the performance of the volumetric system was sensitive to the amount (volume fraction) of the nanoparticles dispersed, in the limit; it resulted in surface absorption for the high volume fraction of the nanoparticles. The study on a thermal battery mimicking a concentrated volumetric solar receiver was conducted by Khalil Anwar et al. (2016). They showed that the aluminum meshes improved the heat diffusion significantly and enhanced the melting rate of the phase change material inside the receiver. This, in turn, minimized the local excessive heating and early initiation of the phase change process inside the thermal battery. The rotation of the receiver reduced the maximum temperature of the working fluid through suppressing local excess heating. In addition, receiver rotation lowered the maximum and minimum temperature difference inside the receiver; however, with increasing rotational speed, a small delay was observed for the time completing the phase change process inside the receiver. The analysis of the performance of a flat-plate volumetric solar collector was carried out by Jeon et al. (2016). They presented the effects of channel depth, channel length, mass flow rate, and the absorption coefficient of the blended plasmonic-nanofluid on the performance of the volumetric solar collector. The volumetric absorption characteristics and optical performance of a solar receiver using a porous media were examined by Chen et al. (2016). They showed that the optical losses due to the back scattering from porous absorber and the absorption and reflection of the solar window had the significant influence on the optical performance of system. The porous structure parameters greatly affected the distribution of the solar radiative source within the porous absorber. In addition, the optical efficiency decreased noticeably when the slope error and alignment error were existed. A multiscale simulation approach of nanofluids for volumetric solar receivers and assessment of inter-particle potential energy was introduced by Cardellini et al. (2016). They represented a first step for a multiscale modelling approach relating the nanoscale properties to the macroscopic behavior of nanofluids. The direct volumetric absorption of a solar radiation was investigated by Hewakuruppu et al. (2015). They indicated that the direct absorbing collectors were possible to maximize the short wavelength absorption while minimize the long wavelength emission from the collector. The volumetric solar heating of nanofluids for direct vapor generation applications was examined by Ni et al. (2015). They demonstrated high nanofluid-assisted vapor generation efficiencies with potential applications in power generation, distillation, and sterilization. The performance of a low-flux direct absorption solar collector using graphite, magnetite and silver nanofluids was studied by Gorji and Ranjbar (2016). They showed that the nanofluids promoted the thermal and exergy efficiencies by 33–57% and 13–20%, respectively than that corresponding to the base fluid. A multi-layer volumetric solar absorber composed of a stack of square grids was examined by Gomez-Garcia et al. (2015). They analyzed the influence of the grid length, the gap between consecutive grids and the wall thickness. They presented the significance of the absorber reflectivity and the effect of the direction of the incident radiation. In addition, a general expression that described the absorption capacity of the absorber and its extinction length was introduced. Investigation of volumetric versus surface solar absorbers for a concentrated solar thermal collector was carried out by Li et al. (2016). The findings revealed that the performance of the volumetric receiver was sensitive to the reflectivity of optical and radiative heat losses from the surface of the glass tube. However, the proposed low-profile collector design was suitable for utilization in industrial and commercial heating applications; however, the volumetric absorbers would require anti-reflective and good selective coatings to be competitive with surface absorbers. Heat transfer analysis of a volumetric solar receiver by coupling the solar radiation transport and internal heat transfer was carried out by Chen et al. (2015). They indicated that the porosity and the mean cell size had a great effect on the distribution of absorbed solar radiation. The silicon carbide ceramic foam for application of a solar volumetric receiver was investigated by Sano et al. (2012). They showed that the pore diameter should be larger than its critical value to achieve high receiver efficiency and there existed an optimal pore diameter for achieving the maximum receiver efficiency under the equal pumping power. A review on volumetric receivers in solar thermal power plants with central receiver system technology was presented by Avila-Marin (2011). They classified chronological the volumetric receivers of most interest for electricity production, identifying their different configurations, materials and real and expected results. They also pointed out important issues surrounding the volumetric receiver, such as the basic plant configuration, flow stability phenomenon and the main problems of a windowed design for pressurized receivers. The optimization study for nanofluid volumetric receivers in relation to the efficiency of the solar thermal energy conversion was carried out by Lenert and Wang (2012). The findings revealed that the efficiency of nanofluid volumetric receivers increased with increasing solar concentration and nanofluid height in the receiver. Radiation heating and fluid flow in ceramic foam volumetric solar air receivers were studied by Wu et al. (2011). They indicated that the macroscopic model could be used to predict the performance of solar air receivers. In addition, the results illustrated that the thermal non-equilibrium phenomena were locally important, and the mean cell size had a dominant effect on the temperature field.

The volumetric solar receivers were studied previously (Cardellini et al., 2016; Chen et al., 2016, 2015; Gomez-Garcia et al., 2015; Gorji and Ranjbar, 2016; Hewakuruppu et al., 2015; Jeon et al., 2016; Khalil Anwar et al., 2016; Khullar et al., 2014; Li et al., 2016; Mey-Cloutier et al., 2016; Ni et al., 2015; Siddiqui et al., 2016; Siddiqui and Yilbas, 2014, 2013; Vakili et al., 2016; Wang et al., 2016) and the main focus was utilizing the absorbing plate in the receiver. However, the effect of the geometric features of the absorbing blocks on the receiver performance was left for the future study. Therefore, in the present study, the solar volumetric receiver with different configuration of the absorber blocks is considered inside the receiver. The performance of the solar volumetric receiver due to various shapes of the blocks is investigated and the effect of solar intensity distribution on the energy gain by the working fluid is examined. In the analysis, volumetric absorption of incident solar radiation is considered and Lambert's Beer law is adopted to determine solar power intensity absorbed inside the volumetric receiver. Four different geometric features of absorbing blocks are selected when assessing the volumetric