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High-Temperature Receiver with a Packed Bed of Transparent Spheres Using CFD Analysis

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Abstract

The interest in high-temperature solar receivers has been being increased over recent years due to the wide applications which such receivers efficiently enable. For example, according to the Sunshot target, to make the Concentrated Solar Thermal (CST) competitive compared to PV and other renewable sources of energy, CST needs to integrate with an advanced power cycle (e.g. combined cycles or the sCO_2 Brayton cycle) which requires above 700C outlet temperature from a receiver [1]. Another application of high-temperature receivers is in the endothermic thermochemical process (e.g. solar fuels and other industrial applications) [2]. However, there is a well-known classical trade-off behaviour in any receivers between outlet temperature and thermal efficiency [3]. When outlet temperature increases, the thermodynamic efficiency significantly decreases due to the re-radiation losses [4]. Another persisting challenge with this push to high temperatures is the capability of the HTF to operate under such high temperatures (e.g. which is currently impossible with the widely used solar salt HTF). Therefore, this pressing new trend needs that the HTF changes from a liquid (i.e. molten salts) to a gaseous or supercritical fluid, due to their high flexibility in high operation temperature [5]. Accordingly, gas-phase volumetric receivers are considered as one of the best available near term solution to achieve this push to high temperatures .

For volumetric absorber, the structured and unstructured packing can be considered as an absorber in the solar receiver/reactor [6]. One advantage with this packed bed absorber is its cost-competitive design and manufacturing compared to other types of the volumetric absorber, including the ceramic or metal foam absorbers [7] and the monolithic honeycombs [8] or such fancy absorber designs of spiked geometry [9] and hierarchically-layered one [10]. Another advantage is that it enables variable optical and thermal properties alongside the absorber via simply filling the bed with particles with different properties. However, a limited study uses a packed bed as an absorber in the solar receiver in literature [11, 12]. This paper aims to benefit from these features of the packed bed to design an inexpensive absorber with a high radiation penetration by using transmittance balls.

Proposed Designs

In this research, a porous absorber design composed of an ordered packing of spherical spheres with different geometric ratios (different ratios of cavity diameter (D) and sphere diameter (d)) is presented. The packed bed was designed with the following options of $\frac{D}{d}$ =3 (7 spheres per layer), $\frac{D}{d}$ =5 (19 spheres per layer), and $\frac{D}{d}$ =7 (37 spheres per layer) and modelled for the same length ($L = 2D$), as illustrated by Figure 1.As a result, the bed options included 6 ($\frac{D}{d}$ =3), 10 ($\frac{D}{d}$ =5) and 14 ($\frac{D}{d}$ =7) layers, with total spheres of 42, 190, 518, respectively. A ray-tracing method and pore-scale CFD model using ANSYS Fluent were employed for this analysis.

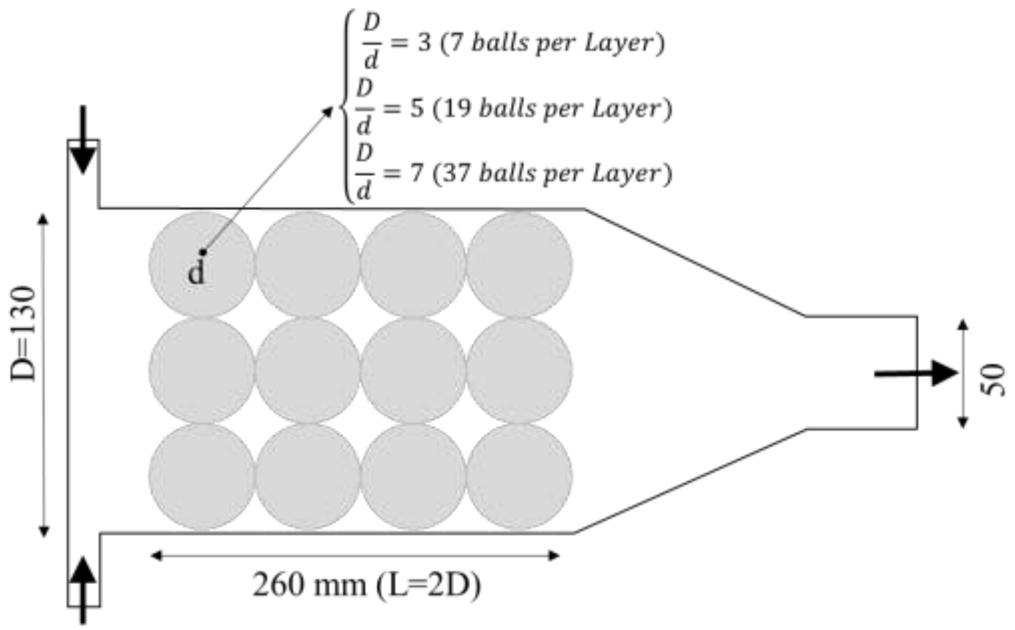


Figure 1. A schematic of the receiver with packed bed of spheres

Ray-tracing analysis

The proposed sphere-containing packed bed absorbers were optically modelled in TracePro. The optical model has been validated in the authors' recent papers [13, 14]. The radiative flux absorbed by the packed bed absorber was computed. The spheres were made of clear quartz with a transmittance of 0.9 and the cavity wall was made of a polished stainless steel. Solidworks was also employed to generate CAD files of these packed bed absorbers, and the ray-independence analysis demonstrated that 1×10^6 rays were suitably sufficient to produce reliable results. **Figure** 2 shows the optical efficiencies of the receiver with and without the conical end. With an increase in the geometric ratio, the optical efficiency of the receiver without the conical base increases from around 71 to 79 %, while the optical efficiency of the whole receiver (which includes both packed bed of spheres and the conical end) almost is constant, starting from 79.7 % at D/d=3, increasing to 80.8 % at D/d=5, before a slight decrease to 80.5 % at D/d=7.

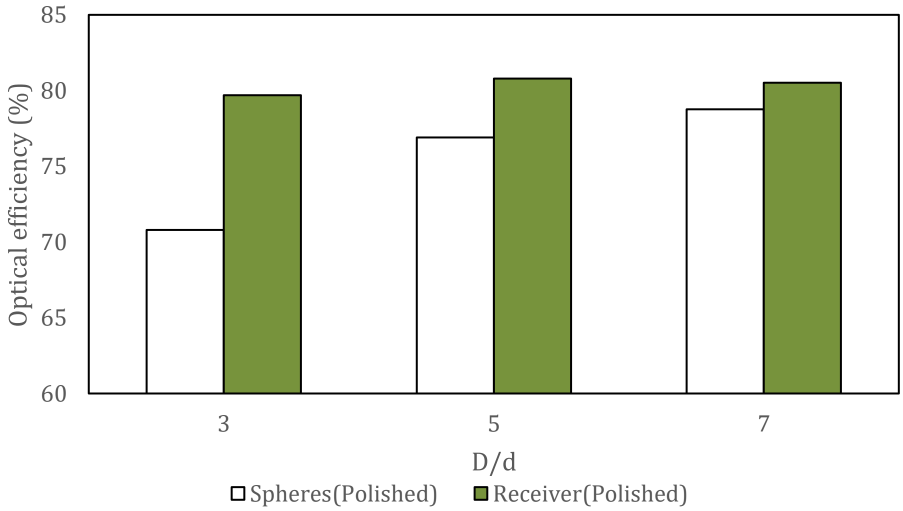
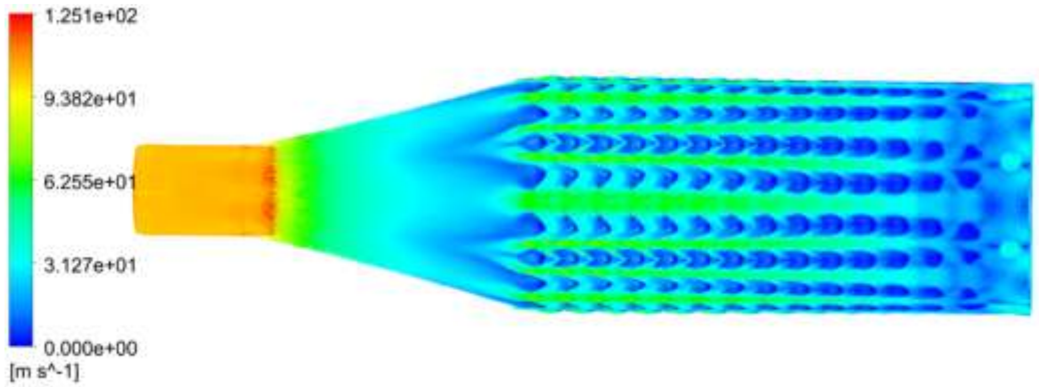


Figure 2. Optical efficiencies of the packed bed and whole receiver (packed bed + conical end) for D/d of 3 to 7.

CFD Analysis

A pore-scale approach was used for this CFD analysis. RNG turbulence model, which researchers have widely used for modelling flow through the packed bed of spheres [12], was used in this study. Polyhedral elements were also utilised. A mass flow rate of 0.075 kg/s was considered for the inlet boundary, and the outlet surface was considered a pressure outlet. The cavity wall was well-insulated, and the radiative flux obtained by the ray-tracing analysis was imported into the CFD model as heat flux boundary conditions. The results demonstrated that the geometric ratio of 5 achieved the maximum outlet temperature above 1000 K (Figure 3) and thermal efficiency due to making a better balance between the optical and thermal losses. These results demonstrate that this inexpensive absorber design of a packed bed of transparent spheres has the potential to enable a high-temperature receiver with high thermal efficiency.

(a)



(b)

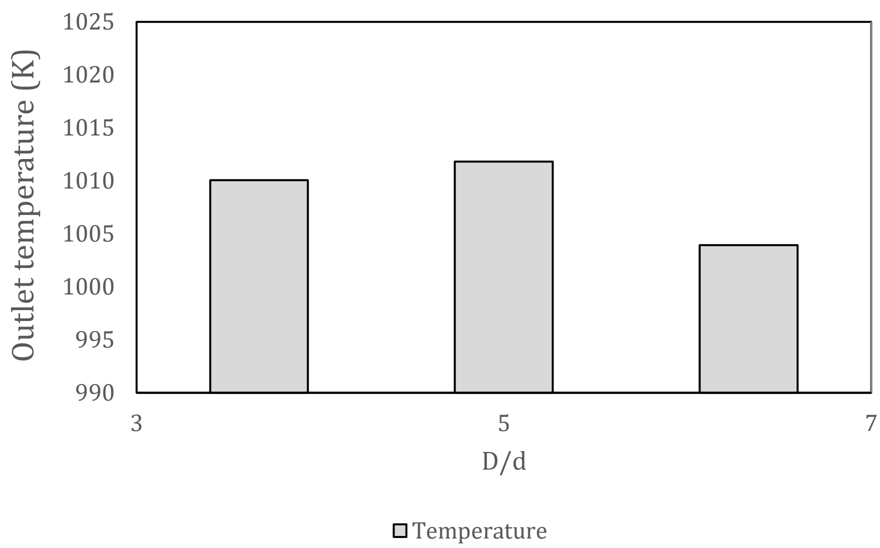


Figure 3. Thermal performances of the proposed receiver: (a) velocity contour of D/d=7, (b) The outlet temperature for D/d of 3 to 7.

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