A comparison of fluidised bed solar receiver geometries

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Introduction

The fluidised bed solar receiver offers a novel method of capturing and harnessing solar energy for utilization. Fluidised bed technology has been extensively studied for many high-temperature heat transfer applications (particularly combustion) and so appears well suited for advanced CSP systems, like tower and beam-down configurations. This could deliver extremely good heat transfer capabilities that conventional receivers using solid particles or fluids flowing inside tubes may not be able to achieve. Likewise, the fluidisation process could reduce the risk of overheated spots and material deterioration due to the continuous particle movement, which helps maintain consistent temperature profiles. Furthermore, the continuous circulation of particles conceivably avoids the buildup of debris, thereby creating a self-cleaning mechanism (Arena, 2013).

The potential benefits of fluidised bed solar receivers have seen them receive some attention in recent years (Bellan et al., 2017) (Tregambi et al., 2019) (Díaz-Heras et al., 2021). These studies have examined the effectiveness of fluidised bed solar receivers and the impact of operational factors such as fluidising gas velocity, particle size and particle type. However, further research is needed to better understand the influence of fluidised bed geometry. As such, this study examined two geometries: square and circular fluidised beds, as previous research has focused on circular beds, whilst square beds are more common in commercial fluidised bed systems.

Method

As noted previously, this work evaluated the effect of fluidised bed solar receiver geometry on the particle volume fractions and bed temperature. Two geometries are investigated: a circular and square bed with adiabatic walls. To undertake this comparison, computational fluid dynamics (CFD) simulations were carried out using a commercial CFD solver (Ansys-Fluent, 2021). The analysis was performed in two stages, the first examined the volume fraction behaviour for 10s under isothermal conditions and without thermal irradiation. The second stage saw the simulation continue with thermal irradiation (to 60s), to study the bed temperatures of both geometries.

In terms of the simulation domains, the circular fluidized bed was assumed to have a diameter of 76.2mm and a height of 500mm, thus matching the geometry of (Díaz-Heras et al., 2020) (Díaz-Heras et al., 2021). The square fluidised bed cross-section was taken to be 67.5mm*67.5 mm with a height of 500mm, this ensure the hydraulic diameter and volume of the two geometries was equal. Additionally, it was assumed that both beds would be loaded with silicon-carbide (SiC) particles, with an initial height of 80 mm. This choice aligns with the work of previous studies by (Díaz-Heras et al., 2020) and (Tregambi et al., 2019) where they investigated different particle materials and determined that SiC particles exhibit favourable characteristics due to their high absorptivity.

An Eulerian-Eulerian approach was employed to simulate the gas-solid multiphase flow, where the Navier-Stokes equations are used to describe each phase's behaviour. Additionally, the P1 radiation model (Ansys-Fluent, 2021) was used to assess the radiation heat transfer to the bed. In saying this, the incident radiation from the top wall, was modelled as a constant high-temperature surface. Finally, it was assumed that airflow at the inlet to the bed was uniform at a velocity of 2 times the minimum fluidisation velocity (U_{mf}), as per Díaz-Heras et al.(2020) experiments, and left the domain through a pressure outlet at atmospheric pressure.

Results

Validation

Before systematically investigating the influence of geometry on the fluidised bed, a simulation of the experimental conditions described by (Díaz-Heras et al., 2020) was undertaken, as a point of comparison. This experiment examined a circular fluidised bed at 2.0U_{mf} with a uniform fluidising air pattern. The results of our simulation are compared with the experimental data in Figure 1. It is apparent that the simulated average temperature over the bed's height deviates slightly from the experimental measurements, though the trend matches relatively well. This suggests that the simulation methodology offers a reasonable approximation of what is observed in reality.

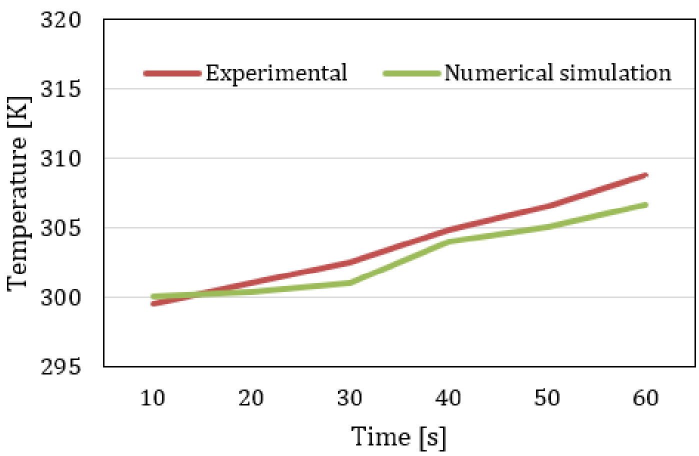

Figure 1. Comparison of bed temperatures from experiments and this simulation

Therefore, having validated the methodology, it was decided to examine some of the parameters that characterise the performance of fluidised bed receivers, namely the volume fraction and bed temperature.

Volume fraction

The volume fraction indicates the ratio of suspended solid particles to the total volume in a fluidised bed, it has a significant effect on the heat transfer efficiency and overall operational characteristics. As mentioned previously, in this study a simulation was carried out to evaluate the volume fraction deviation between the circular and square fluidized beds, for a 10 s interval. Figure 2 shows the volume fraction contours of both bed geometries.

These figures demonstrate the passage of the fluidising gas through the bed, which takes on distinct patterns as a result. In the circular bed, the process initiates with small, narrow bubbles distributed near the bed's base (Fig 2-A). Over time and with continued gas injection the bubbles increase in size around the bed's middle (Fig 2-B). Some bubbles coalesce, forming circular gas bubbles just below the bed's top prior to eruption (Fig 2-C).

Conversely, the fluidizing gas initiates with elongated, flat bubbles within the square bed configuration (Fig 2-D). These bubbles progressively expand while maintaining their shape until reaching the middle of the bed (Fig 2-E), and as they approach the bed's upper region, the bubbles transform into a more rounded form (Fig 2-F). In saying this, it is also worth highlighting that the corners exhibit the highest particle volume fraction, which has implications in-terms of the circulation of particles in the bed. Furthermore, it is worth noting that the highest gas velocity through the square bed was approximately 0.5 m/s higher than the circular bed, despite both beds having the same initial fluidization velocity.

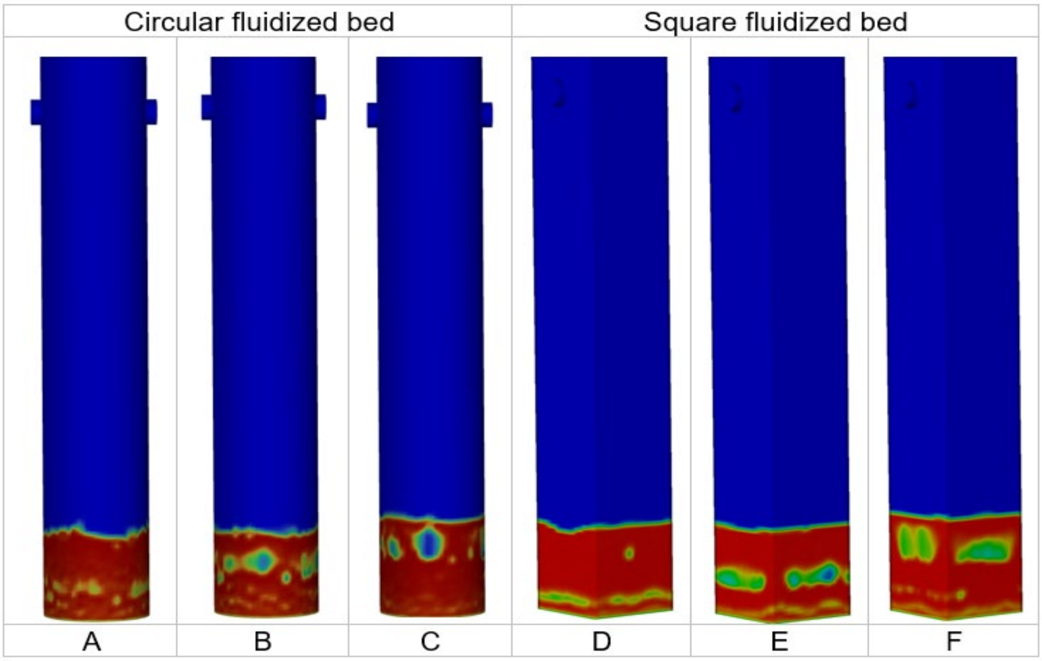

Figure 2. Volume fraction snapshots for circular and square fluidized bed

Bed Temperature

Additional investigation was carried out to assess the impact of different bed configurations on bed temperature. To achieve this objective, a simulation was conducted for a duration of 60 seconds. The results presented in Figure 3, display the particle temperature distribution across the top cross-section of the fluidised bed.

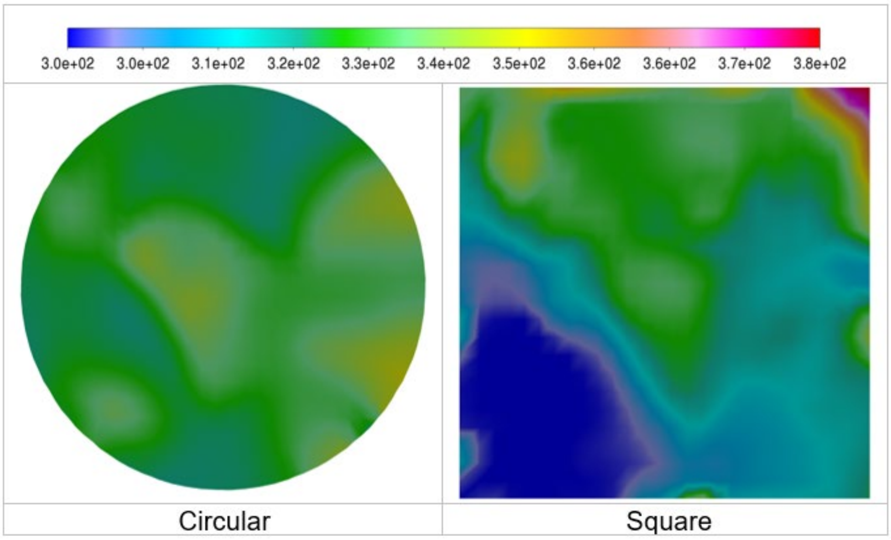

Figure 3. Top of the fluidized bed temperature contours

In the circular bed, the variation in temperature across the bed is relatively small, with no pronounced hotspots observed. Conversely, the square bed exhibits broader temperature fluctuations, with the highest temperature occurring at the corner and cooler areas as well. In this sense these results are to be expected, based on the volume fraction observations. Furthermore, whilst one could be concerned about the impact these temperature profiles have on the performance and operation of the fluidized bed receiver, at the larger scales one would expect of a commercial CSP receiver, these corner effects are likely to be less significant.

Future work

The present study was conducted using a small-scale fluidized bed receiver. The outcomes suggest a preference for the circular shape; however, further investigation is necessary to assess its implications on a larger, commercial scale, where outcomes might differ. Additionally, it's important to account for factors such as non-uniform incident radiation and non-uniform fluidized gas.

Conclusion

This study investigates how different fluidized bed geometries impact the particle volume fraction and bed temperature within a fluidized bed receiver. The research explores two small geometries: circular and square. To validate the numerical model, the obtained results were compared with previous findings, demonstrating reasonable agreement. When taking a broader perspective, the results imply that:

- In the circular bed, the bubbles' size is comparatively smaller and more confined compared to the square fluidized bed.
- The circular bed exhibited a higher average temperature than the square bed. However, the square bed had a higher maximum bed temperature.
- There is a likelihood of hot spots emerging in a square bed which could affect bed performance, receiver operation, and durability if not accounted for at full scale.

In conclusion, it is worth noting that the current study focused on a uniform fluidizing gas pattern. And despite the potential issues in square beds, the ease of manufacture 'at scale' of such systems means that they appear to be an attractive solution. In saying this, strategies such as introducing a non-uniform gas supply in these square beds could be used to establish a more even temperature distribution throughout, whilst also mitigating the occurrence of hot spots. In this sense square beds would seem to warrant further attention.

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