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Numerical simulation of particulate flow in interconnected porous media for central particle-heating receiver applications

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Abstract

The use of central solar particle-heating receivers (SPR) in concentrated solar power (CSP) systems offers numerous advantages over other central receiver concepts. The two main advantages are: (1) ordinary particulate minerals can allow collection temperatures approaching 1000 °C compared with conventional molten salts which are limited to about 650 °C, and (2) the low-cost high temperature particulate material can also be used as the storage medium in a highly cost effective thermal energy storage system. An innovative SPR design invented by researchers at King Saud University and Georgia Institute of Technology allows the particulate material to flow downward through a stationary porous structure where the concentrated solar energy is absorbed. The porous structure reduces the speed of the falling particulate material, i.e. increases its residence time within the receiver, thereby allowing a large temperature rise to be achieved in a single pass. The design increases absorption of the incident solar radiation (i.e. receiver efficiency) and reduces convective heat loss and particle loss (Al-Ansary et al., 2013). A numerical two-fluid solid–gas Eulerian–Eulerian flow model has been used to evaluate the effect of the porous structure on particulate flow through the receiver. The stationary porous structure was modeled using the packed bed concept in the FLUENT commercial CFD code. Two benchmarking experiments were conducted to assess the validity of the two-fluid flow and packed bed model for flow through the porous structure. This paper describes the two benchmarking experiments, and provides a comparison between the model predictions and the measured data. In the first experiment, particle flow rates through variable-width slits at the bottom of a constant head plenum were measured. In the second experiment, a porous layer was placed above

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the opening at the bottom of the constant head plenum to limit the particle discharge flow. Experiments with two different porous layer heights were conducted using two particle materials with different diameters and densities. The simulation results were in reasonable agreement with the test data.

Keywords: Concentrated solar power; Particle heating receiver; Numerical simulation; Particulate flow; Granular flow; Porous structure

1. Introduction

Concerns regarding climate change due to high levels of CO_2 emissions, coupled with the rise in fossil fuel costs and heightened concerns regarding the safety of nuclear power, have motivated increased research and development efforts on renewable energy sources in many countries around the world. As a part of these efforts, a 300 kW_{th} concentrated solar power (CSP) test facility is being constructed at the Riyadh Techno Valley development on the campus of King Saud University (KSU) in Riyadh, Saudi Arabia (Golob et al., 2014). The system uses a central receiver power tower as the energy collection subsystem and a gas turbine as the power conversion subsystem.

Among the unique features of this facility is that the energy collection and storage medium will be solid particles (for example sand or other granular material). Solar radiation incident on a heliostat field is concentrated on a receiver through which the sand flows by gravity and is heated to as high as 1000 °C. In addition to serving as the heat collection medium, the sand also serves as the thermal energy storage medium by directing the solar-heated sand exiting the receiver to an insulated storage bin. The sand leaving the bottom of the hot storage bin flows over a heat exchanger where heat is transferred from the sand to the gas turbine cycle working fluid (air). A multi-pass, finned-tube, cross flow heat exchanger will be used for initial testing of the KSU CSP test facility. Other heat exchanger designs, including a direct-contact heat exchanger and a fluidized bed heat exchanger will be evaluated. The KSU system design avoids the temperature limitations and high costs of conventional heat transfer fluids and storage media. It also does not require water cooling; hence, it alleviates many of the obstacles and objections to increased use of CSP in desert environments.

Work on the KSU CSP test facility builds on earlier research on solar particle heating receiver (SPR) concepts, particularly the work of Sandia National Laboratory (Martin and Vitko, 1982; Chen et al., 2006; Ho et al., 2009; Siegel et al., 2010; Ho and Iverson, 2014). Several other direct (Wu et al., 2014) and indirect receiver (Diver, 1987; Glatzmaier, 2011) concepts have also been reported in the literature. The KSU system design overcomes the shortcomings identified by Sandia regarding SPR technology. Specifically, the SPR in the KSU system allows the particulates to flow through a porous structure or a series of chevron mesh screens (instead of a free-falling curtain), thereby significantly increasing the particles' residence time within the receiver (Al-Ansary et al., 2013). This, in turn, allows the desired temperature rise of the particle stream (e.g. increase from ~600 °C at the inlet to 1000 °C at the exit) to be readily achieved without the need to recirculate the particles through the receiver cavity prior to transferring them to the hot storage bin. Additionally, the KSU SPR design significantly decreases convective heat losses (because of the reduction in heat transfer area), as well as material (i.e. particulate) loss from the receiver, thereby increasing the receiver efficiency (Golob et al., 2014).

The sand exiting the heat exchanger accumulates in a "cold" (i.e. ~600 °C) storage bin from which it is returned to the top of the receiver via a variable-speed particle lift. While the operational control strategy for the KSU facility has not been fully developed, it is expected that, for part-load operation, the lift speed (i.e. the particles flow rate) will be controlled to maintain the desired receiver outlet temperature.

Several studies have been made to investigate the behavior of falling particles within solid particle heating receivers. Chen et al. (2006) used computational fluid dynamics (CFD) to determine the velocity and temperature distribution within a free-falling particle receiver. Their analysis is limited to cases where the solid particle volume fraction inside the solar absorber is very low. In a follow-up study, Siegel et al. (2010) tracked the particle motion and the gas flow within a free-falling solid particle receiver. They compared their simulation results against experimentally-measured velocity and temperature distributions and showed good agreement. The particle volume fractions in their simulation are still relatively low (<10%). Grena (2009) treated the stream of solid particles as a single-phase fluid within the solar absorber and determined the resulting velocity and temperature distributions for different particle sizes and radiation exposure times.

None of the models reported in the literature to date addresses the unique aspects of the KSU SPR design, namely, the interactions between the particles and the stationary porous structure (or sequence of mesh screens) through which they flow. Most prior models assume a relatively low particle volume fraction, and therefore, cannot be expected to accurately model the particle/particle and particle/structure interactions within the KSU SPR design. Slowing down of the particles as they flow through the porous structure leads to significantly higher particle volume fractions (within the interstitial regions of the porous structure). Additionally, while a portion of the concentrated solar power incident on the receiver is directly absorbed