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A study of granular flow through horizontal wire mesh screens for concentrated solar power particle heating receiver applications – Part I: Experimental studies and numerical model development

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ABSTRACT

A proposed design for a concentrating solar power (CSP) receiver uses granular material – such as sand – as the heat transfer and energy storage medium. Early designs of particle heating receivers (PHR) utilize a falling curtain of particles which directly absorbs the concentrated solar radiation. However, falling curtain receivers have several disadvantages including significant heat and particle losses and short residence time within the irradiation zone. One design proposal which overcomes these challenges is the so called "impeded flow PHR design", in which the particles flow over, around, or through a series of obstacles in the flow path. This reduces the average velocity of the particles, thereby increasing their residence time in the irradiation zone of the receiver. It also reduces heat and particle losses from the receiver. However, granular flows through complex structures are not well understood, rendering a priori design of impeded flow PHR geometries difficult. To better understand these flows, lab scale models of a PHR design variant using horizontal wire mesh screens have been constructed, allowing granular flows through the receiver geometry to be experimentally analyzed. In addition, two different numerical modeling approaches – the discrete element method (DEM) model, and a two-fluid computational fluid dynamics (CFD) model – have been developed to model the flow of particles through the specified receiver geometry. The results of the DEM model are in reasonable agreement with the experimental data with respect to mass flux, and better matches the experimental data than the CFD model. A companion paper presents parametric studies to assess the sensitivity of model predictions to various design and modeling parameters (Sandlin and Abdel-Khalik, 2017).

1. Introduction

The use of concentrated solar power (CSP) for electricity production has received increasing amounts of research and public interest in recent years (Behar et al., 2013). The renewable nature of the energy source and the lack of pollution during operation are the two chief advantages of CSP.

CSP takes on several forms, including parabolic trough designs, Fresnel lens reflectors, and solar power towers (Zhang et al., 2013). All CSP technologies operate using the same principles: using mirrors, the incident solar radiation is focused onto a receiver where a heat transport medium, such as water, pressurized air, or a liquid salt solution, is used as a coolant. This medium can then be used to generate electricity using a typical power cycle, or can store that heat to enable power generation during periods of no solar input.

Many current forms of CSP which include heat storage use a molten salt solution to store the solar energy. While these designs enable the use of current technology to store and move the heat transfer fluid, there are several drawbacks: the molten salt solution itself is relatively expensive, corrosive, and has a relatively narrow range of operating temperatures of roughly 250–620 °C (Zhang et al., 2013).

One proposed approach uses a granular material - such as sand - as the heat transfer and storage medium. Not only would such a system be cheaper and safer, but would potentially offer much higher temperature limits, increasing thermodynamic efficiency.

The use of solid particles for a heat transfer and storage medium has been under investigation since the early 1980's (Martin, 1982). Extensive research in the area of falling curtain solid particle receivers has been performed (Falcone et al., 1985; Chen et al., 2007; Kim et al., 2009; Kim et al., 2010; Khalsa et al., 2011; Röger et al., 2011; Ho et al., 2014b; Gobereit et al., 2015; Zanino et al., 2016), as the design is relatively simple, yet allows for direct heating of the particles by concentrated solar irradiation. However, falling particle curtain designs share a common disadvantage: particle hydrodynamics play a large role

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in receiver design and particle selection because of convective heat losses and mass losses from the curtain. In fact, particle aerodynamics and heat transfer performance may be at odds, as smaller particles absorb heat faster via irradiation, but also lose heat faster due to convective losses, and are more easily blown around by air currents in the receiver. Larger particles can be used to offset some of the particle loss issues, but their higher terminal velocity means that residence time in the receiver is shorter, leading to lower heat absorption (i.e. a lower temperature rise across the receiver). Some of the proposed falling particle designs use particle recirculation systems to overcome this issue, but that adds mechanical complexity and parasitic load. The recirculation system also needs to be carefully controlled to ensure high efficiency (Gobereit et al., 2015).

One proposed receiver design to overcome these issues is a so called impeded flow particle heating receiver (PHR). In this receiver design, particles flow over a series of obstacles in the flow path. In one rendering of such a design, the particles flow through a porous ceramic foam structure (Al-Ansary et al., 2017). This design should greatly reduce the issues related to particle loss and convective loss by controlling maximum particle velocities and an overall reduction in air velocity within the particle flow zone in the receiver cavity. The reduction in maximum particle velocity also increases the residence time of particles in the irradiated zone, allowing high particle temperatures to be achieved without complicated particle recirculation systems. An impeded flow PHR should also allow greater control over local values of solids volume fraction within the receiver aperture, as the solids fraction must increase as the average particle velocity decreases, relative to a fixed granular mass flux. However, impeded flow PHR designs are expected to have an upper limit on both granular mass flux and local solids volume fraction they can support, based on the specific geometry chosen design variant and the granular material in use, and may thus require a larger cross sectional flow area to achieve a target mass flow rate compared to a falling particle curtain. As the total mass flux of a PHR system is a function of particle density, velocity, solids volume fraction, and the overall cross section of the flow area, the limits of a given impeded flow PHR design need to be understood to enable the successful design of a commercial scale system.

On sun testing of another design variant of an impeded flow PHR which uses angled wire mesh screen structures has shown that it does offer advantages over simple falling particle curtains with respect to particle temperature rise and overall receiver efficiency, without the need to incorporate complex recirculation systems (Ho et al., 2016a; Ho et al., 2016b). However, the testing has also revealed challenges in materials selection and understanding granular flow through these complex geometries. While there have been numerous studies on predicting the rate of granular flow through simple structures such as hoppers (Fowler and Glastonbury, 1959; Beverloo et al., 1961; Jenike, 1961; Brown and Richards, 1965; Savage, 1965; Crewdson et al., 1977; Williams, 1977; Nedderman et al., 1982; Gu et al., 1992; Gu et al., 1993; Weir, 2005; Tighe and Sperl, 2007; Hilton and Cleary, 2011; Janda et al., 2012; Oldal et al., 2012), no general continuum analysis of granular flows through complex structures, such as those envisioned for impeded flow PHRs, appears to exist at present (Abrahamsson et al., 2014).

Several numerical studies have been reported in the literature on the use of computational fluid dynamics (CFD) simulations of falling curtain PHR designs (Chen et al., 2007; Kim et al., 2009; Kim et al., 2010; Khalsa et al., 2011; Ho et al., 2014b; Gobereit et al., 2015). However, the granular flow conditions present in a falling curtain are expected to be very different than in flow through complex geometric structures such as in impeded flow PHR designs. In particular, several of the previous studies have used a discrete phase model (DPM). A DPM simulation typically assumes very low particulate volume fractions (<10%), and particle interactions are often ignored (Dickenson and Sansalone, 2009). Both of those conditions are expected to be locally violated in an impeded flow PHR.

Numerical simulation of an impeded flow PHR has only begun very recently. Lee et al. (2015) performed a two-fluid study of granular flow through a porous foam structure. However, instead of simulating the foam structure itself, the structure was replaced with a simpler packed bed geometry, meaning that the particle scale flow characteristics were not maintained in the simulation.

The discrete element method (DEM) (Cundall and Strack, 1979) is a Langrangian method for modeling granular flow in that it tracks individual particles. It has been used to model granular flows through complex geometries, including wire mesh screens (Cleary and Sawley, 2002; Delaney et al., 2012; Dong et al., 2013). Cleary and Sawley (2002) performed an early study of a polydisperse granular material flowing through a horizontal vibrating screen. While that study was mostly qualitative in nature, it served to establish DEM simulations as a useful tool for studying complex granular flow processes. Delaney et al. (2012) performed a DEM study of an angled vibrating screen to simulate a granular screening and classifying process. They showed good agreement between experimental and simulated data at low simulated particle feed rates onto the angled screen, but found that high simulated particle feed rates led to excessive blocking of the screen openings due to the spherical nature of the simulated particles (a physical process called blinding (Advantech, 2001)). Dong et al. (2013) also performed a DEM study of an angled vibrating screen. By counting particle-screen collisions, an estimate of the probability of a particle passing through the screen was developed. In each of these studies, segregation performance of the screen was the main objective of the study. However, in an impeded flow PHR, segregation is not desired in order to avoid localized overheating and lowered efficiency due to non-uniform particle distribution within the receiver aperture. It has recently started being investigated for use in a falling curtain PHR design, but the simulated particles were much larger than the actual particles in order to ease computational requirements (Zanino et al., 2016).

With no general analytic way to predict granular flow through complex structures, and no numerical modeling of the granular flows of interest, the goals of this study were twofold. First, lab scale test sections of representative impeded flow PHR design variants were constructed and flow tested to determine the particle flow characteristics. Second, numerical models of the experimental granular flows were conducted using two different methods – the discrete element method (DEM), and a CFD/finite volume method – to not only validate one or both of the numerical models, but to determine the suitability of one or both models for future use in more complicated designs. In this paper, experimental studies for one PHR design variant (multiple parallel horizontal wire mesh screens) and associated numerical models are presented. The focus of this paper is on the experimental and numerical mass flux through the impeded flow PHR geometry; further analysis is given in Sandlin (2017). A companion paper (Sandlin and Abdel-Khalik, Submitted for publication) presents studies to assess the sensitivity of the numerical model predictions (both DEM and CFD) to various design and modeling parameters.

2. Experimental setup

The main goals of the experimental setup were to allow rapid changes in test section configuration, and to enable the measurement of experimental data, primarily the mass flux, that could also be evaluated in the numerical simulations. The main features of the experimental setup included a particle storage hopper, a small "upper section," the main test section, a collection bucket, and the necessary control valving and instrumentation. The purpose of the upper section was to reduce any entrance length effects in the main test section; thus, it had the same configuration as the main test section. Fig. 1 shows the location of the main components of the experimental apparatus.

To investigate the performance of the specific PHR design variant of interest, a lab scale test section was constructed to allow qualitative and quantitative evaluation of the granular flow through the horizontal